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CONTENTS

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CORRECTION

MONTHLY WEATHER REVIEW, June 1950, vol. 78, p. 97: In paragraph 1, line 16, the phrase "between 200 and 500 feet" should be corrected to read "between 2,000 and 5,000 feet".

DEPARTMENT OF COMMERCE
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ATMOSPHERIC OZONE AT WASHINGTON, D. C.

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ABSTRACT

Total atmospheric ozone measurements at Washington, D. C., for the period February 18, 1948, through March 9, 1950, are tabulated and described. The usual annual variation is found. The average amount of ozone observed for the 2 years is somewhat low for 39° N. latitude.

Ozone departures from normal in relation to surface low and high pressure systems are analyzed. The distribution around Lows agrees quite well with most other analyses. Around Highs the distribution is poorly defined, and is considerably different from results at other geographical areas.

Correlations of ozone with temperatures at the 500-mb. and 100-mb. levels are examined. The correlation coefficients vary regularly from month to month, and there is a suggestion that their highest absolute values occur in some spring and winter months, and that the lowest absolute values occur in summer and early autumn. Two possible explanations of this variation are discussed, namely, (1) the annual cycle of the variability of ozone and of temperature, and (2) the annual change of the winds above 18 km.

CONTENTS

INTRODUCTION

Relatively few comprehensive analyses of total atmospheric ozone measurements have been made in North America, although in recent years a few studies have been made in the United States [1, 2]. Thanks to New York University for a loan of their Dobson ozone spectrophotometer (No. 19), the United States Weather Bureau has been making regular ozone measurements in Washington, D. C. (lat. 38°54′ N., long. 77°3′ W.) whenever practicable since February 1948. The results of these measurements will be presented here.

METHOD OF OBSERVATION

THE INSTRUMENT

The Dobson spectrophotometer has already been described [3] and will be mentioned only briefly. In order to increase the sensitivity of the instrument so that measurements of the vertical distribution of ozone could be made, the electrical portions of the instrument were completely redesigned [4] by the Naval Research Laboratory, and a photomultiplier was substituted for the original photocell,[1]

[1] The following is quoted (slightly modified as shown by brackets) from a letter by Dr. Dobson dated August 15, 1950, and received after this manuscript had been submitted for publication:

"Since multipliers have become commercially available . . ., the photocell has [generally] been replaced by a multiplier. It is understood that this has also been done for most of the older instruments in Europe and that all new instruments are fitted with multipliers."

but the optical portion of the instrument was not changed.

The instrument operates fundamentally by comparing the intensities of two wavelengths of *direct* sunlight, namely I=intensity at wavelength 3110A and I'=intensity at wavelength 3300A; I is strongly decreased through absorption by ozone, while I' is only slightly affected by ozone. A dial is attached to an optical wedge which varies I' until its electrical response equals that due to I, at which time a galvanometer indicates a zero reading. The instrument is calibrated so that, except for constants which cancel out in the end, the dial reading gives $L=\log_{10}(I/I')$. By taking dial readings over a large range of solar altitudes, a graphical plot of L against μ can be made, where μ is the optical path through the ozone layer, the vertical path being taken as unity. Once an "appropriate" height of the ozone "layer" is chosen (we used 20 km.), μ depends on the solar altitude. On days when ozone changes very little, this graph of L vs. μ will be a straight line, and extrapolation to $\mu=0$ gives $L_0=\log_{10}(I_0/I'_0)$, the value of L "outside" the earth's atmosphere. Except for instrumental changes, L_0 is assumed to remain constant with time. Moreover, instrumental changes which affect L_0 can be checked periodically with lamps which have been supplied with the instrument.

CALCULATION

Having determined L_0 and L, the total amount of ozone, x, in a vertical column above the observer [5] is given by

$$x=\frac{L_0-L}{1.17\mu}-0.085 \qquad (1)$$

The unit of x (or O_3) is the centimeter; i. e., the height which a column of ozone of unit cross section would occupy if it were reduced to standard temperature and pressure. The 0.085 is a factor which is supposed to take account of differential scattering of energy in the two wavelengths by air molecules and by dust. Actually the instrument contains provision for examining the intensity of a third wavelength, I'' at 4450A, which together with I' should yield information about the change in the dust scattering from observation to observation. But dust scattering is improperly understood at present, and several different formulae have been used from time to time to account for it. However, all the Washington data presented here have been calculated from equation (1).

Equation (1) applies only to observations made by utilizing direct sunlight. With reduced accuracy, the instrument can also be used in the daytime during overcast conditions, when the sun is not visible, but only direct solar measurements have been included in this paper. During some of our observations the sky was indeed overcast, but the sun's disk was visible and the energy received by the instrument was sufficiently intense to make a dial reading possible.

ACCURACY OF THE OBSERVATIONS

The accuracy of an ozone observation depends on (1) the accuracy in setting the dial (or wedge), (2) the accuracy of L_0 and (3) the effect of dust and other atmospheric contaminants.

DIAL SETTING

Dobson [3] found that the effect of dial setting introduced a negligible error, and this appears to be true also of our observations. Our practice is to make three dial readings in the space of about one minute, the average of the three readings comprising a single observation. If we assume that the amount of ozone does not change appreciably in one minute, the greatest difference between any two of the three dial readings indicates the error due to dial setting. On the average, we found the difference to correspond to about 0.002 cm. of ozone.

VALUE OF L_0

At irregular intervals, values of L_0 were determined by making series of observations during one day, and also by checking with the lamps. We found that sometimes L_0 did change. In September 1948, following a period during which the instrument had been transported for use at White Sands, N. Mex., L_0 changed for an undetermined reason. Although the instrument had not been moved from Washington after June 1949, on December 6, 1949, the dial readings and hence the L_0 underwent a marked permanent change, which presumably was due either to a slippage of the connection between the dial and the wedge, or to some discontinuity in the photomultiplier response. However, this change was abrupt and very obvious, so that an appropriate L_0 could be determined and applied to the observations following December 6. For reference purposes, the individual values of L_0 and the values which we used (generally an average of the values in any period) are given in table 1. On several

TABLE 1.—*Values of L_0*

Date	L_0	L_0 used
1948		
Feb. 27	2.666	Feb. 18, 1948 through July 6, 1948: 2.619
Mar. 1	2.581	
Mar. 5	2.620	
June 8	2.609	
Sept. 1	2.685	Aug. 31, 1948 through Dec. 5, 1949: 2.680
Sept. 13	2.676	
Oct. 26	2.702	
Oct. 27	2.687	
Dec. 7	2.732	
1949		
Mar. 29	2.667	
Mar. 30	2.677	
July 27	2.680	
July 28	2.680	
Aug. 25	2.650	
Aug. 29	2.680	
Aug. 30	2.652	
Sept. 2	2.674	
Sept. 9	2.698	
Sept. 20	2.677	
Sept. 21	2.684	
1950		
Jan. 24	2.800	Dec. 6, 1949 through Mar. 9, 1950: 2.800
Jan. 26	2.805	
Mar. 6	2.800	

occasions calibrations with the lamps offered supplementary values for aid in evaluating the finally used values of L_0. Since equation (1) also involves μ, the maximum error due to inaccuracies in L_0 is probably of the order of 0.01 cm. of ozone.

DUST

Equation (1) does not allow for changes of dial reading caused by changes in "dust" although several different ways of allowing for dust have been used in the past [6]. The dust effect is complicated and improperly understood, and it appears that the error introduced by use of equation (1) in comparison with the formula of Ramanathan and Karandikar [6] usually is less than 0.01 cm. (at least for India), although on very hazy days it may reach 0.02 cm.

In summary, it seems that a difference of 0.01 cm. or less between two observations, taken on different days or in different months, is of doubtful reality, and perhaps on occasion a difference of 0.02 cm. or even more may be caused by something other than a change in ozone.

THE OBSERVATIONS

As mentioned earlier, each observation consists of three dial readings taken in rapid succession. For each day, the observations have been averaged and these average values appear in table 2 and in figure 1. Table 2 also contains the number of observations in each day and the range of the ozone values, that is, the difference between the highest and lowest ozone values observed on the particular day.

The solid curve in figure 1 represents the average annual variation, and was determined by eye (with minor adjustments) from a plot of 10-day mean values of ozone overlapping by 5 days. The curve shows many of the

TABLE 2.—*Daily ozone values*

Date	Average ozone (0.001 cm.)	Number of observations	Range (0.001 cm.)	Date	Average ozone (0.001 cm.)	Number of observations	Range (0.001 cm.)
1948				*1948*			
Feb. 18	196	22	29	June 17	226	2	15
19	207	2	2	22	208	11	----------
26	230	3	5	24	208	7	6
27	215	9	17	25	222	4	26
Mar. 1	211	12	11	28	209	7	8
5	198	9	17	29	225	3	33
8	237	4	15	30	212	9	9
10	224	3	4	July 1	209	2	2
12	210	5	45	6	198	1	----------
15	212	2	0	Aug. 31	222	7	10
May 10	225	4	26	Sept. 1	215	25	9
11	224	2	11	2	214	3	8
12	208	4	20	3	210	3	49
13	214	1	----------	4	223	2	3
18	276	2	5	6	205	3	2
19	256	3	12	8	202	4	7
20	254	2	9	9	224	3	18
21	241	5	7	12	199	3	1
24	240	2	21	13	210	26	24
25	229	1	----------	14	214	3	4
27	231	1	----------	15	221	3	36
28	230	2	19	16	234	6	53
June 1	253	1	----------	17	226	3	5
2	267	3	20	20	209	2	6
4	238	6	8	23	198	3	16
7	222	2	0	27	200	4	10
8	224	25	16	28	192	2	10
9	246	9	9	29	190	3	1
10	244	19	19	Oct. 1	193	2	1
11	222	9	13	7	201	3	14
14	228	4	6	12	187	11	24
15	220	4	9	14	194	16	30

TABLE 2.—*Daily ozone values*—Continued

Date	Average ozone (0.001 cm.)	Number of observations	Range (0.001 cm.)	Date	Average ozone (0.001 cm.)	Number of observations	Range (0.001 cm.)
1948				*1949*			
Oct. 15	173	2	1	July 18	199	4	3
18	208	1	----------	19	211	4	9
19	213	3	4	20	207	2	4
20	195	2	1	21	209	2	1
21	202	6	9	22	206	3	18
25	176	4	11	25	216	3	3
26	176	21	7	26	223	1	----------
27	175	21	10	27	212	34	13
28	194	4	2	28	218	23	11
29	220	2	20	29	215	2	21
31	190	1	----------	Aug. 1	227	2	11
Nov. 4	183	4	9	4	200	2	13
8	177	3	2	8	236	3	10
10	153	3	1	9	217	3	10
12	154	3	5	10	220	3	20
16	167	2	0	11	224	2	15
17	173	4	6	12	222	2	2
18	175	5	9	16	205	4	6
20	153	1	----------	19	215	3	20
23	161	1	----------	22	211	5	31
26	167	2	3	23	201	1	----------
27	158	2	4	24	210	3	10
30	186	1	----------	25	218	12	22
Dec. 1	192	2	14	26	207	2	3
2	187	3	15	29	191	12	6
6	174	3	4	30	206	19	18
7	179	18	6	Sept. 1	204	5	9
9	194	1	----------	2	207	22	7
10	243	5	4	6	201	1	----------
13	188	5	15	8	214	5	13
14	185	3	4	9	211	22	13
17	182	3	5	12	197	5	3
20	234	2	1	13	192	3	3
21	185	4	7	15	197	4	12
22	194	5	3	19	200	7	6
23	178	3	3	20	212	17	13
24	177	3	6	21	200	50	11
27	221	4	3	22	206	7	13
28	200	4	9	26	208	4	9
31	216	2	6	30	189	5	23
1949							
Jan. 3	185	3	10	Oct. 3	181	2	0
6	179	10	13	4	180	5	3
7	203	3	5	5	196	1	----------
10	230	1	----------	10	176	4	5
11	181	3	3	11	172	10	9
12	225	2	4	12	173	4	9
13	221	6	5	18	185	2	8
14	201	2	1	20	175	2	15
Feb. 15	172	2	6	21	179	2	10
17	218	4	6	24	190	1	----------
18	213	2	10	26	196	3	13
23	226	2	7	27	195	4	24
24	208	3	10	Nov. 2	183	3	26
25	215	2	3	9	211	1	----------
Mar. 1	269	2	1	14	172	2	4
2	255	3	7	15	182	2	14
4	236	2	4	17	223	3	5
7	259	3	24	18	234	2	2
8	206	3	14	21	194	3	4
9	215	1	----------	22	209	3	2
14	231	2	3	23	188	2	2
16	274	3	18	25	215	1	----------
21	212	2	4	28	189	1	----------
23	217	3	12	30	191	3	3
29	217	20	22	Dec. 1	198	2	7
30	216	9	12	5	222	2	5
Apr. 4	236	3	11	6	231	1	----------
6	252	3	2	7	239	1	----------
7	245	2	0	8	249	1	----------
8	289	5	5	9	270	1	----------
15	220	3	13	10	236	1	----------
19	262	4	15	14	206	2	3
20	237	4	3	15	199	1	----------
21	241	3	1	17	200	2	0
25	218	4	9	20	227	1	----------
28	229	3	15	21	212	1	----------
29	243	3	3	28	214	2	9
May 4	265	4	16	29	232	2	2
5	241	2	7	30	228	2	3
				1950			
6	233	3	9	Jan. 6	186	1	----------
9	212	4	10	9	211	1	----------
12	245	5	28	10	196	4	5
13	266	3	17	11	212	2	2
17	251	3	7	18	187	1	----------
18	232	5	4	23	212	1	----------
19	219	3	0	24	226	8	14
20	211	2	1	25	219	4	10
23	234	4	16	26	198	14	7
24	235	3	2	Feb. 3	229	14	17
25	235	4	11	8	250	7	12
27	254	2	3	15	203	1	----------
31	249	4	13	20	259	5	16
June 1	275	4	21	21	231	3	13
July 5	243	2	7	23	251	2	6
6	232	3	14	27	290	2	12
8	222	3	4	Mar. 1	239	1	----------
11	221	2	2	2	301	2	2
13	213	2	2	6	232	33	6
14	221	3	9	7	230	1	----------
15	218	1	----------	9	254	3	8

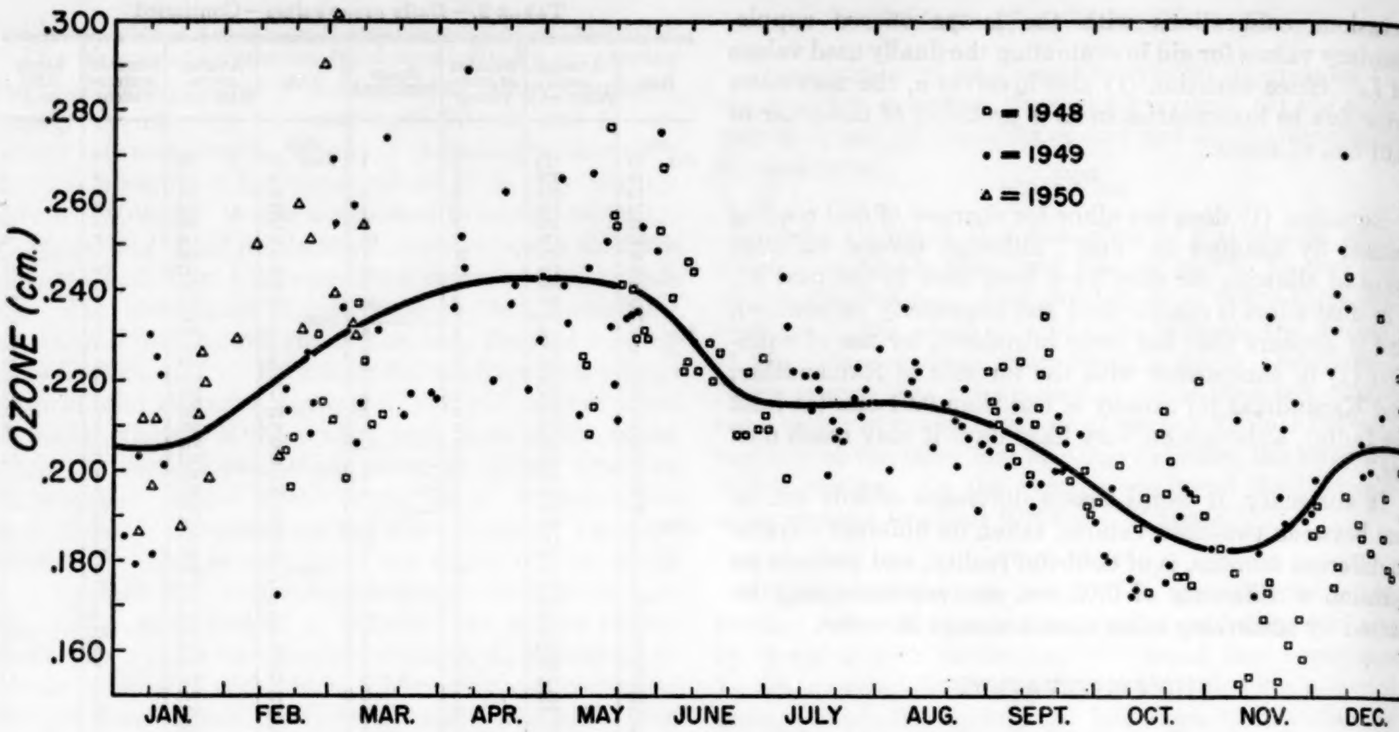

FIGURE 1.—Daily average ozone observations (symbols) and "normal" annual ozone distribution (curve).

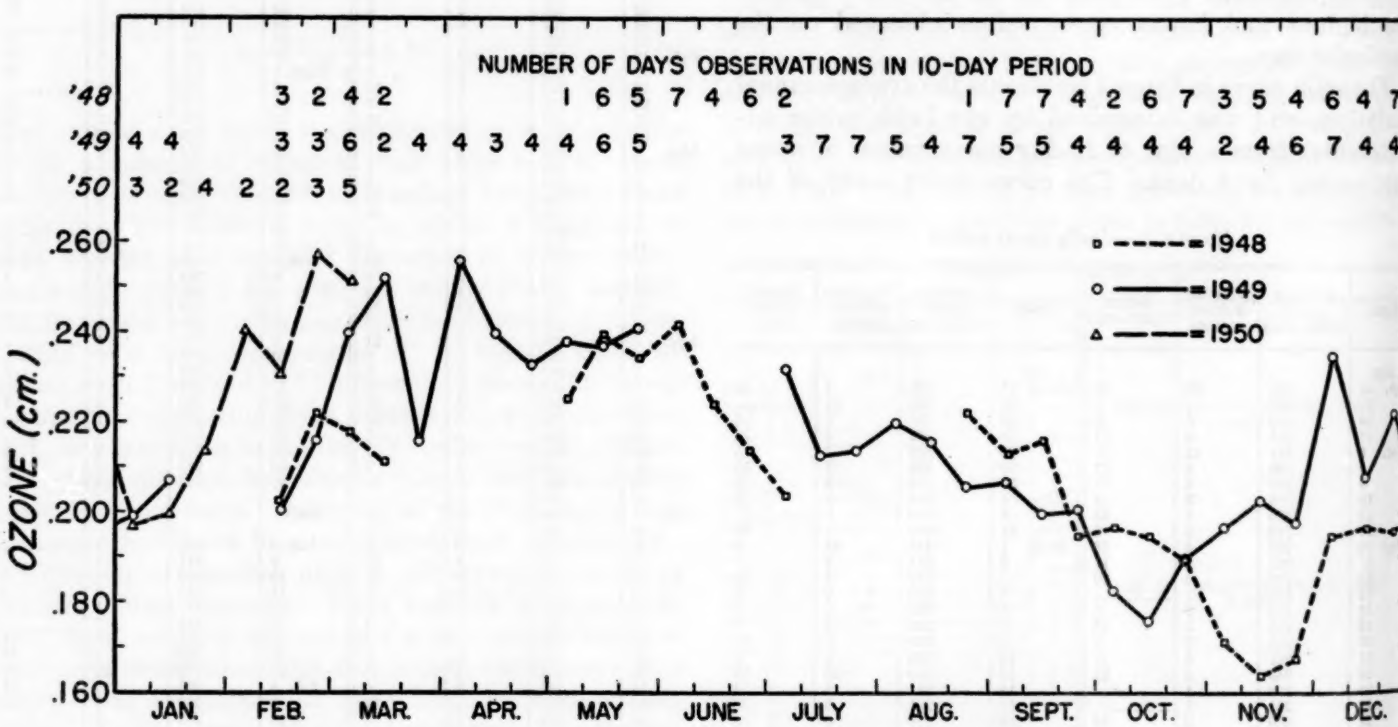

FIGURE 2.—Ten-day mean values of ozone and number of days of observations.

usual features. The annual trend is quite evident, showing the maximum in the spring and the minimum in the fall. The plateau in August is similar to that found by many observers [7], but the plateau in December–January is apparently not generally observed. It remains to be seen of course whether anything except the over-all annual trend will remain after more data have been obtained. By comparison with data from Craig's [7] graphs, it is found that the curve is about 0.02 cm. below the average for about latitude 40° N. in all seasons, but is very close to a curve of the minimum values for that latitude. The curve differs markedly from Stair's [2] values, being about 0.04 cm. lower in January, and about 0.035 cm. higher in August.

As usual, the scatter seems to be greatest in spring, although November 1949 also showed considerable scatter. We shall return to this point later.

Figure 2 shows the individual 10-day means (not overlapping), together with the number of days in each 10-day period on which observations were made. In general, the different years show some marked differences, and some interesting similarities. The two Mays have about the same average value in spite of the great daily variability (fig. 1) but the two Novembers are rather different. In 1950, the data start out with the same value as for January 1949, but in February 1950, the mean value is considerably higher than in 1949.

DISTRIBUTION OF OZONE AROUND SURFACE PRESSURE SYSTEMS

LOW PRESSURE SYSTEMS

Dobson, Harrison, and Lawrence [8] (D. H. L.) showed that, on the average, ozone tended to be distributed in a definite manner in relation to surface low and high pressure systems. For cyclones, Meetham [9] extended their findings, and later Dobson, Brewer, and Cwilong [10] (D. B. C.) amplified the earlier results by separating Lows into (a) "young depressions" and (b) "old occluded depressions." In the occlusions, which they say had only cold air associated with them, the highest ozone was found *in*, and *in advance of*, the low center; only *above* normal ozone values appeared in occlusions. In the young depressions, with open warm sector, the highest ozone appeared to the west of the low center, and the lowest values appeared over the surface warm front.

Tønsberg and Olsen [5], observing in Tromsø, Norway, also related their ozone data to surface low pressure systems, and by contrast to the (D. B. C.) results found *no* above normal values for a thousand miles in advance of the surface position of the occluded front; in advance of the occlusion, and in a few cases even behind it, only below normal values were observed. For the case of the open wave cyclone, their results agree fairly well with those of (D. B. C.). As a matter of fact, in the Tromsø results there is little difference between the occluded and open wave cyclone ozone distributions.

Using the technique of Meetham, and of Tønsberg and Olsen, the Washington ozone data were analyzed as follows. On each day during which one or more ozone observations had been made, namely, on the dates in table 2, the 1800 GMT North American surface weather map was examined. If a well-developed low center was present, and if Washington lay inside the area encircled by a cyclonic isobar, Washington was considered to be under the influence of the cyclone. On some occasions Washington lay between a deep Low and a well-developed High; the nearly straight isobar through Washington did not immediately enclose either pressure system, but rambled around several systems. In these cases, Washington was considered to be under the influence of both the cyclone and the anticyclone. Two intersecting perpendicular lines were drawn on a sheet of translucent paper, as shown by the north-south and east-west lines in figure 3. The translucent paper was then placed on the weather map with the intersection over the low center, and the perpendicular lines were placed tangent to the latitude line and along the longitude line through the low center. The position of Washington was then marked on the translucent paper; and, considering the curve of figure 1 to be the normal, the departure from the normal ozone for that day was written near the position of Washington. Occasionally, the Low was of questionable dominance, or it was not clear that Washington was under the influence of the Low; these cases have been marked with a question mark (?) in figure 3. Very questionable cases were discarded.

The results are shown in figure 3 where, for emphasis, all departures of less than 0.01 cm. in absolute value were deleted because the sign of smaller departures is in some doubt. It should be noted that these data do not represent the ozone distribution around a single cyclone, nor do the isolines represent average values of ozone departure; the isolines have been included to facilitate visual examination of the magnitudes. But, insofar as cyclones are similar to each other, the "average" pattern of ozone distribution may be found by this technique. The similarity to the pattern of Tønsberg and Olsen, to that of (D. H. L.) and, for open wave cyclones, to that of (D. B. C.) is quite striking. Although there is no single center of maximum ozone departure, for this group of relatively large departures there is a broad region to the west of the cyclone where, without exception, the ozone was above its normal value; to the east, only below normal values are found. As was the case for the Tromsø data, negative values were associated with occlusions (in at least two cases) as well as with open wave cyclones.

As for the distance from the cyclone center, Meetham [9] had found the maximum ozone departures in a region

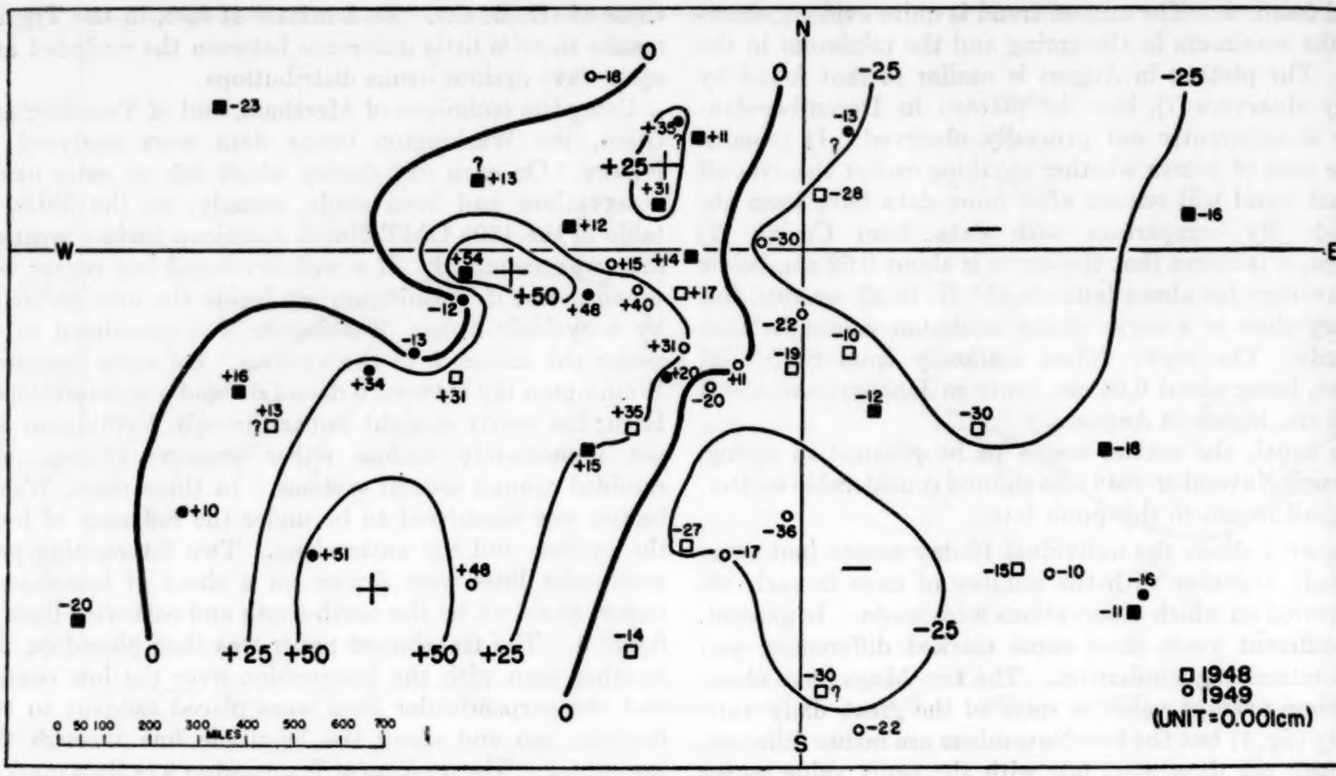

FIGURE 3.—Ozone departures from normal distributed relative to surface *low* pressure systems; departures with absolute values smaller than 0.01 cm. are excluded. Solid symbol represent cases which appear also in figure 4.

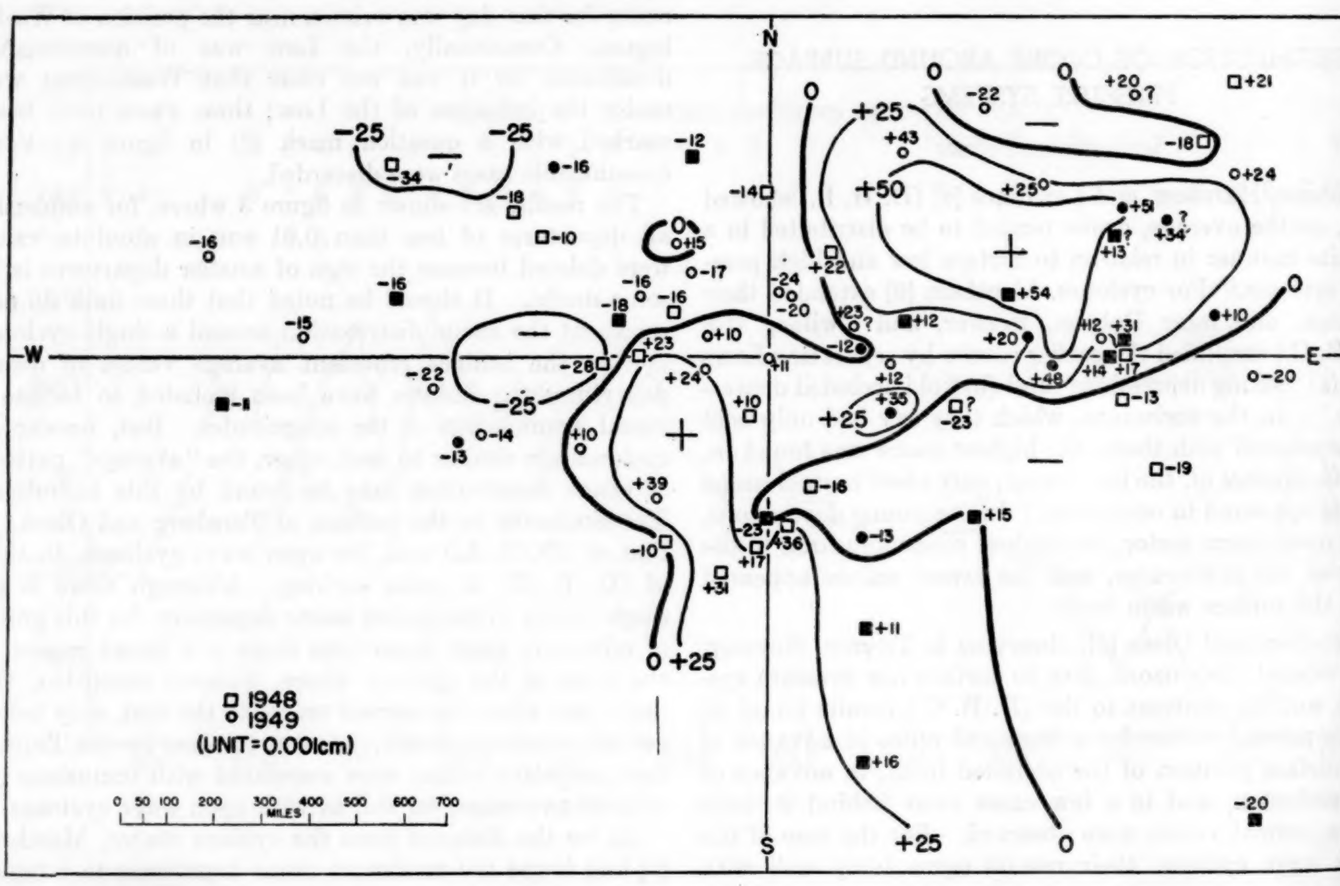

FIGURE 4.—Ozone departures from normal distributed relative to surface *high* pressure systems; departures with absolute values smaller than 0.01 cm. are excluded. Solid symbols represent cases which appear also in figure 3.

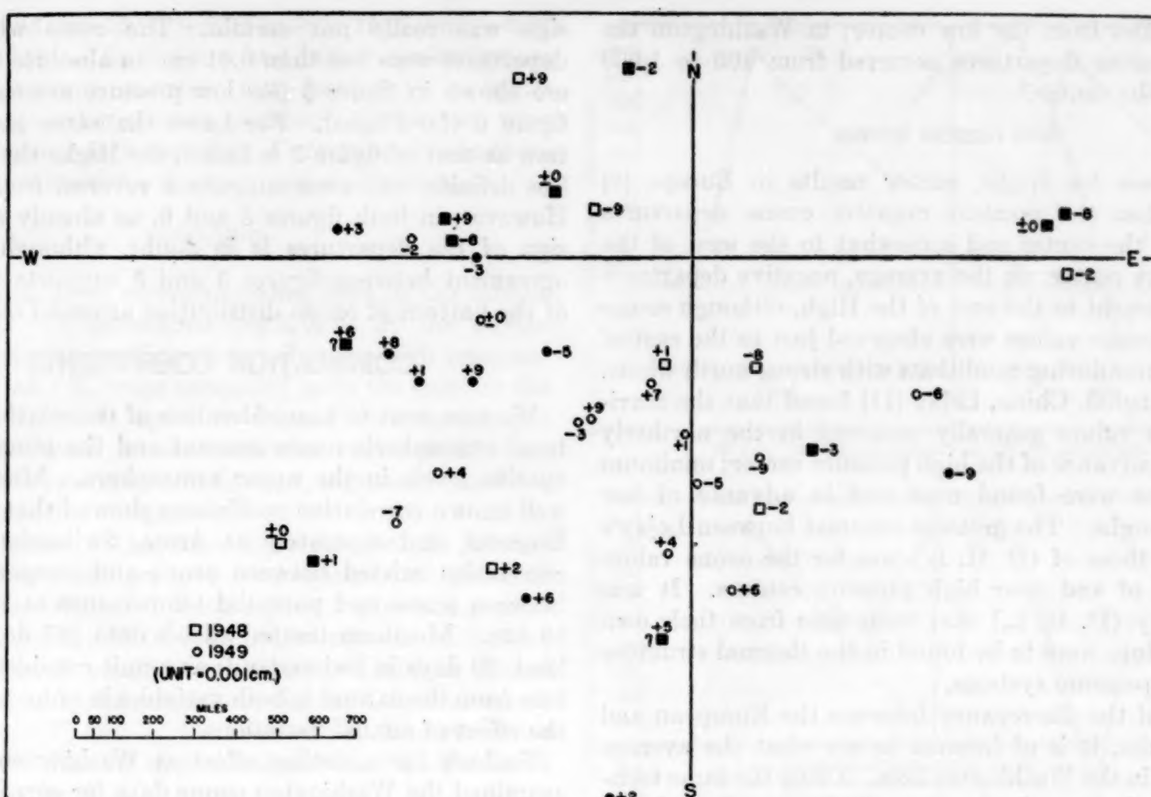

FIGURE 5.—Ozone departures from normal with absolute values less than 0.01 cm. distributed relative to surface *low* pressure systems. Solid symbols represent cases which appear also in figure 6.

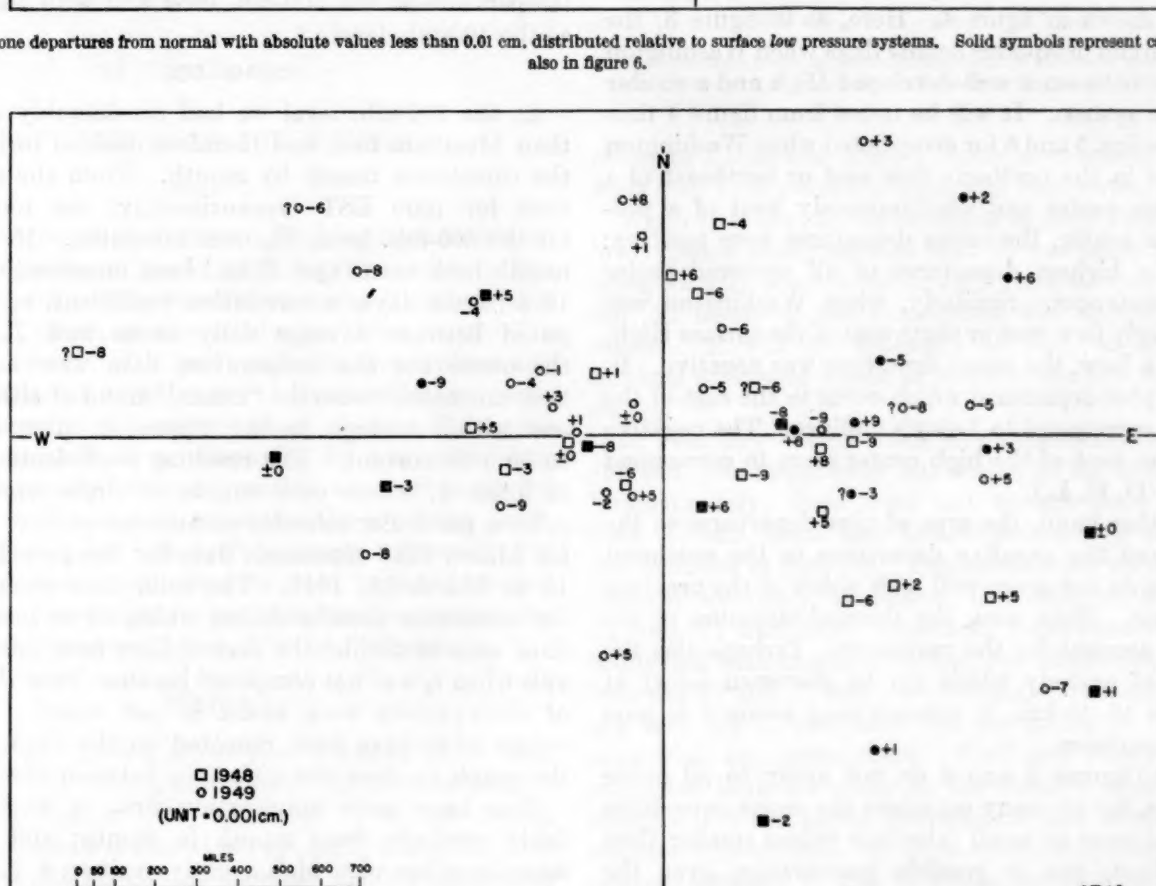

FIGURE 6.—Ozone departures from normal with absolute values less than 0.01 cm. distributed relative to surface *high* pressure systems. Solid symbols represent cases which appear also in figure 5.

0 to 400 miles from the low center; in Washington the maximum ozone departures occurred from 400 to 1,000 miles from the center.[2]

HIGH PRESSURE SYSTEMS

In the case for Highs, earlier results in Europe [8] indicated that the greatest negative ozone departures occurred in the center and somewhat to the west of the high pressure center; on the average, negative departures also were present to the east of the High, although sometimes high ozone values were observed just to the east of the high center during conditions with strong north winds.

Near Shanghai, China, Lejay [11] found that the maximum ozone values generally occurred in the northerly flow just in advance of the high pressure center; minimum ozone values were found near and in advance of low pressure troughs. The greatest contrast between Lejay's results and those of (D. H. L.) was for the ozone values in advance of and near high pressure centers. It was suggested by (D. H. L.) that variations from their own average picture were to be found in the thermal structure of the high pressure systems.

In view of the discrepancy between the European and Asiatic results, it is of interest to see what the average condition is in the Washington area. Using the same technique as in the case for low pressure systems, we found the results shown in figure 4. Here, as in figure 3, the blackened circles or squares denote days when Washington was situated between a well-developed High and a similar low pressure system. It will be noted from figure 4 that as a rule (see figs. 5 and 6 for exceptions) when Washington was situated in the northerly flow east or northeast of a high pressure center and simultaneously west of a pronounced low center, the ozone departures were positive; actually, the highest departures of all occurred under these circumstances. Similarly, when Washington was in the southerly flow west or northwest of the surface High, and east of a Low, the ozone departure was negative. In general the plus departures which occur to the east of the high center correspond to Lejay's findings. The negative values to the west of the high center seem to correspond to those of (D. H. L.).

On the other hand, the area of plus departures to the southwest and the negative departures to the southeast of the Highs do not agree well with either of the previous investigations. Here, also, the thermal structure of the Highs may account for the variations. Perhaps also the prevalence of easterly winds (to be discussed later) at levels above 18–20 km. in summer may account in part for these departures.

Of course, figures 3 and 4 do not apply to all ozone observations, for on many occasions the ozone departures from normal were so small (absolute values smaller than 0.01 cm.) that, due to possible inaccuracies, even the sign was really not certain. The cases when ozone departures were less than 0.01 cm. in absolute magnitude are shown in figure 5 (for low pressure systems) and in figure 6 (for Highs). For Lows the same general pattern as that of figure 3 is found; for Highs the pattern is less definite, and even suggests a reversal from figure 4. However, in both figures 5 and 6, as already stated, the sign of the departures is in doubt, although the good agreement between figures 3 and 5 supports the reality of the pattern of ozone distribution around Lows.

CORRELATION COEFFICIENTS

We turn next to a consideration of the relation between total atmospheric ozone amount and the temperature at specific levels in the upper atmosphere. Meetham's [9] well-known correlation coefficients showed that at Oxford, England, and separately at Arosa, Switzerland, a high correlation existed between ozone and temperature and between ozone and potential temperature at 12, 15, and 18 km. Meetham treated all his data (37 days in England, 30 days in Switzerland) as a unit considering departure from the normal in both variables in order to eliminate the effect of annual variations.

To look for a similar effect at Washington, we have examined the Washington ozone data for correlation with temperature at the 500-mb. level and with temperature at the 100-mb. level.

500-MB. LEVEL

At the 500-mb. level we had considerably more data than Meetham had, and therefore decided to investigate the correlation month by month. From the radiosonde data for 1000 EST (approximately) the temperatures for the 500-mb. level, T_5, were tabulated. If in any one month both ozone and T_5 had been measured on at least 10 separate days, a correlation coefficient, r_5, was computed between average daily ozone and T_5. Neither the ozone nor the temperature data were adjusted to their normals because the "annual" trend of either parameter within a single month appeared, after inspection, to be unimportant. The resulting coefficients are shown in figure 7, where each square or circle represents the r_5 for a particular calendar month, except that the square for March 1948 represents data for the period February 15 to March 15, 1948. The solid lines connect points for *consecutive* months during which 10 or more pairs of data were available; the dashed lines pass through intervals when r_5 was not computed because fewer than 10 sets of observations were available per month. The 1948 values of r_5 have been repeated on the 1949 portion of the graph to show the difference between the two years.

Two facts seem noteworthy; first, r_5 seems to vary fairly regularly from month to month; and second, r_5 sometimes has very high negative values; e. g., -0.96 in March 1949 and -0.90 in May 1948. On the other hand, the value of r_5 is sometimes near zero; e. g., $+0.08$

[2] Culnan [1, p. 21] states, ". . . it appears that the large departures from normal ozone occur further to the rear of pressure systems at New York than in Western Europe."

in February–March 1948, +0.24 in July 1949, and −0.27 in August 1949. The 2 years had rather similar values during the autumn months, but seemed to be quite different in the other seasons as though the pattern were displaced about 2 to 3 months. Unfortunately, in those seasons, r_5 was available for both years only in May.

100-MB. LEVEL

The 500-mb. level represents conditions in the middle troposphere. To investigate conditions in the stratosphere, correlation coefficients, r_1, of ozone with temperature at 100 mb., T_1, were computed as in the case for the 500-mb. level, where again 10 sets of observations per month were chosen as the minimum required number. The values of r_1 are shown in figure 8, together with the r_5 data of figure 7 for comparison.

Here, of course, we have fewer suitable months because the radiosonde data are not as frequently obtained at 100 mb. as at 500 mb. Each square represents a computed value for r_1; when consecutive months of r_1 were lacking, adjacent points were connected with a dotted line. As might be expected from the usual inverse correlation between T_5 and T_1, the left-hand scale of ordinates (500-mb. level) has the opposite sign from the right-hand scale (100-mb. level).

Although there are some marked differences between the two curves, the main features [3] were maintained at both the 500-mb. and 100-mb. levels.

DISCUSSION OF THE RESULTS

FIGURE 7

Figure 7 shows that in certain months, such as March 1949 for example, r_5 has a high negative value. This means that during those months whenever T_5 is low (cold troposphere), ozone is almost always high; when T_5 is high, ozone is low. It's as though the troposphere and ozonosphere (much of which lies in the stratosphere) were geared in some way; a motion which changes the tropospheric temperature is accompanied by a corresponding (but not necessarily identical) motion which changes the total ozone by the correct amount. On the other hand, in the months when r_5 is low, T_5 is largely independent of ozone. Apparently, motions in the troposphere are independent of ozonospheric motions; the troposphere and portions of the stratosphere seem to be "ungeared".

FIGURE 8

By and large, figure 8 shows that r_5 and r_1 follow each other closely, but with opposite sign. In months when r_1 is high, as in March 1949, whenever T_1 is high (warm stratosphere), ozone is almost always high; when T_1 is low, ozone is low. And from this, together with the discussion

[3] Culnan [1], using 16 km. temperatures, found $r=+0.55$ for December–May, and $r=+0.28$ for June–November.

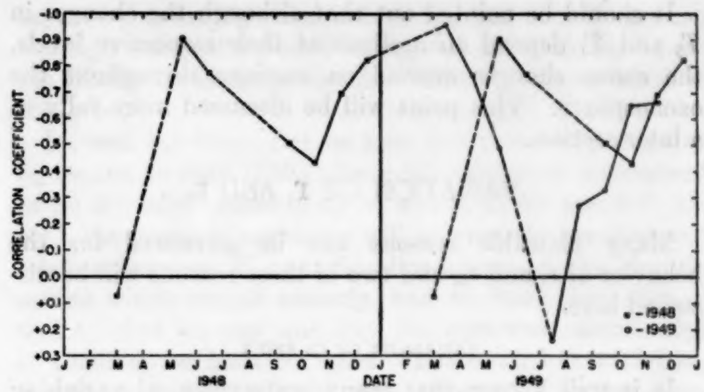

FIGURE 7.—Annual march of correlation coefficients of total ozone with temperature at 500 mb.; 1948 data are repeated on right for comparison.

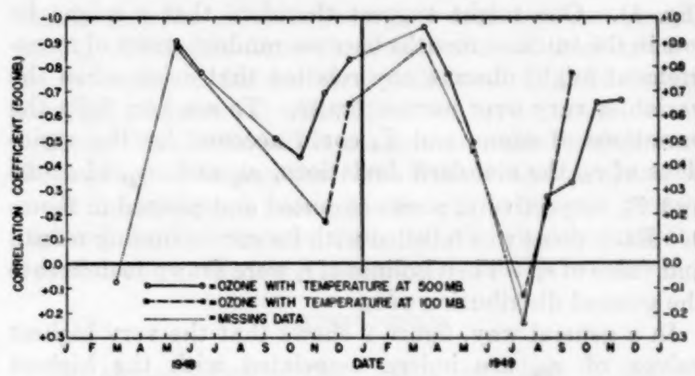

FIGURE 8.—Annual march of correlation coefficients of total ozone with temperature at 100 mb. (right-hand ordinate); 500-mb. coefficients (fig. 7) are included for comparison (left-hand ordinate).

of figure 7, the well known result is obtained that when T_5 is low, T_1 is generally high, and vice versa.

When r_5 is low, as for example in July 1949, r_1 is also low. But a study showed that T_5 was fairly well correlated with T_1 ($r=-0.64$) in July 1949, so that up to 100 mb. all layers of the atmosphere did appear to act in unison. It will be necessary to look to atmospheric motions at higher levels to explain the low values of r_1 and r_5.

In February–March 1948, the atmosphere even up to 100 mb. was apparently not acting in its usual manner. Unfortunately, there were not enough days on which both T_1 and ozone had been measured, so that r_1 was not included in figure 8. But considering all days in the interval February 15–March 15, 1948, on which both T_1 and T_5 had been measured, regardless of whether ozone had been measured or not, the correlation coefficient between T_1 and T_5 was low (−0.34), indicating that even the very low stratosphere was not acting in correspondence with the troposphere. Wulf and Obloy [12] have suggested that, especially in the vicinity of low pressure troughs, a warm arctic stratosphere may overlie a warm tropical troposphere. In such cases, of course, the usual relation between T_1 and T_5 would not be found, and perhaps such a process was operating in February–March 1948.

It should be pointed out that although the changes in T_5 and T_1 depend on motions at their respective levels, the ozone changes depend on motions throughout the ozonosphere. This point will be discussed more fully in a later section.

VARIATION OF r_1 AND r_5

Many plausible reasons can be advanced for the behavior of r_1 and r_5, and two of these reasons will be discussed here.

VARIABILITY OF O_3 AND T

It is well known that many meteorological variables such as temperature, vary less in summer than they do in other seasons, and to an extent this is also true of ozone (fig. 1). One might suggest therefore that r might be low in the summer months because random errors of measurement might obscure any relation that exists when the variables vary over narrow limits. To see how fully the variations of ozone and T_5 could account for the variations of r_5, the standard deviations, σ_{O_3} and σ_{T_5}, of ozone and T_5, respectively, were computed and plotted in figure 9. Each point was labelled with its corresponding month and value of r_5. Then isolines of r_5 were drawn to delineate the general distribution of r_5.

In a general way, figure 9 shows that the very highest values of σ_{O_3} are indeed associated with the highest absolute values of r_5, and, with a few exceptions (notably February–March 1948), the lowest values of σ_{O_3} and/or σ_{T_5} are related to low absolute values of r_5. But within this general framework there are several noteworthy discrepancies. For example, although both Mays had rather similar values for σ, their values of r_5 differed considerably (−0.90 in 1948, and −0.49 in 1949); on the contrary, although both Novembers had quite similar values for r_5, their values for σ differed appreciably. Despite the paucity of data at 100 mb., by and large, similar results are found when σ_{T_1} and r_1 are utilized. At 100 mb., as perhaps in figure 9, the results are somewhat independent of σ_T, but r_1 varies regularly with σ_{O_3} except that for September 1949, r_1 did not fit the general pattern at all. So, while the over-all annual variations of σ_{O_3} and σ_{T_5} may account for the variation of r_5 from month to month, the whole variation of r_5 can perhaps not be attributed to the variations in σ, or by implication, to our inability to measure changes in ozone when the total range of ozone changes is relatively small.

ANNUAL VARIATION OF WINDS ALOFT

Aside from any seasonal change in the standard deviations, there is an observed annual variation in the high-level winds which suggests advection as a physical reason for the major variation of r_5 and r_1.

The role of advection in the local variation of temperature and of ozone is shown in equations (2) and (3). The local variation of temperature, $\frac{\partial T}{\partial t}$, at the 500-mb. level, neglecting non-adiabatic effects, depends only on motions at that level and may be expressed [13] by

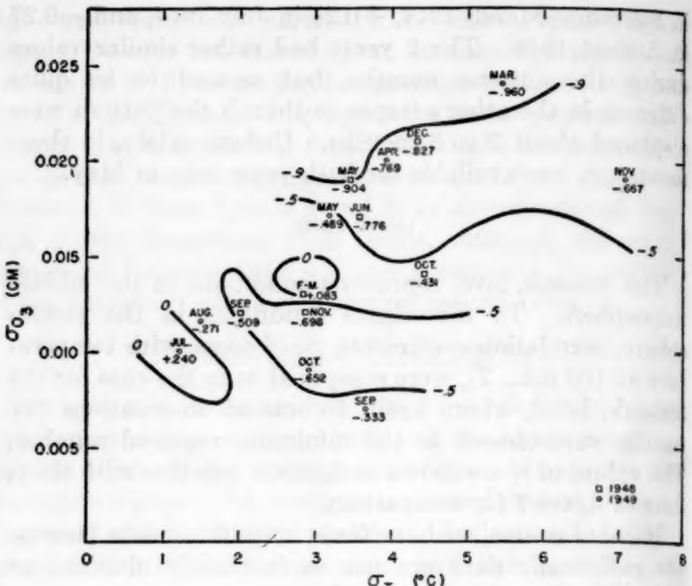

FIGURE 9.—Relation between r_5 and standard deviations (σ) of ozone and T_5. Numbers entered near the points and the isolines represent values of r_5.

$$\left.\frac{\partial T}{\partial t}\right]_5 = -\nabla_h T\cdot V_h\Big]_5 - V_z(\Gamma-\gamma)\Big]_5 \tag{2}$$

where $-\nabla_h T$ is the horizontal temperature gradient and V_h is the horizontal wind vector, V_z is the vertical wind velocity, Γ is the dry adiabatic lapse rate and γ is the actual lapse rate. A similar equation would obviously apply for T_1.

The variation of total ozone is made up of changes occurring at all levels. This is shown in figure 10 b, c. Figure 10b [14] shows the distribution of ozone vertically above Arosa, Switzerland (lat. 47° N.) for a "typical" low ozone day (0.200 cm.) and for a "typical" high ozone day (0.300 cm.). Similarly, figure 10c [15] shows the vertical ozone distribution for typical low (0.155 cm.) and high (0.217 cm.) ozone days at Delhi, India (28.5° N.). Presumably the corresponding ozone distribution at Washington (39° N.) would be similar to either the Arosa or the Delhi distribution or to both. Note that by no means does all of the change in ozone from a low ozone day to a high ozone day take place below 18 km.; a substantial portion of the change occurs above 18 km.

The time variation of total ozone, neglecting local production or destruction of ozone, except that due to vertical motions aloft,[4] is

[4] Nicolet [16] suggests that convergence or divergence associated with vertical motion may change the amount of ozone. This effect has been neglected here.

$$\frac{\partial O_3}{\partial t}=\int_0^{50 km} -\nabla_h(O_3)_z\cdot V_h dz-\int_{30 km}^{50 km} f[(O_3)_z, V_z, z]\, dz \qquad (3)$$

where $-\nabla_h(O_3)_z$ is the horizontal gradient of ozone at a particular height, z; and $f[(O_3)_z, V_z, z]$ is some unknown function of $(O_3)_z$ and V_z, and z. Here $(O_3)_z$ is the density of ozone (cm./km.) at the height z. The second term on the right is integrated from 30 km. to 50 km. for reasons which will be mentioned later.

ADVECTION

$|r_1|$ *and* $|r_5|$ *high.*—In the months when r_1 and r_5 have high absolute values, $|r_1|$ and $|r_5|$, then T_5, T_1 and O_3 vary together in a manner to be expected qualitatively from advection alone.

Whereas, in middle latitudes, *below* 18 km. both in the stratosphere and troposphere the wind direction is westerly in all seasons; *above* 18 km. there seems to be a well defined seasonal reversal of the observed wind direction in the ozonosphere (see for example [17, 18, 19, 20]; see also [12]). The wind *above* 18 km. is westerly from autumn through early spring; but in spring, the wind becomes easterly and in the summer, above 18–20 km. it remains easterly to the top of the observations which on occasion reach to 37 km. [19].

In the westerly current, that is, in winter at all elevations and in summer below 18 km., the direction of the north and south component of the air is usually (but not always) maintained at all heights from at least the 500-mb. level and above. Now, the first terms on the right of equations (2) and (3) express the advectional change in T and O_3 respectively; and these terms indicate that the change in T is due to advection at only one level in the atmosphere, but the change in O_3 is caused by the advection summed over all levels from the ground to about 50 km.

Let us consider March 1949. If we apply the north wind condition shown schematically in figure 10a, we should expect that the entire column of air up to "great" heights would be brought toward Washington from the north by the winds, bringing with it its temperatures and ozone content (fig. 10b,c) at all heights. If further, we accept Meetham's results, that to the north of Washington ozone and stratosphere temperatures are already highly correlated, then obviously $|r_1|$ and $|r_5|$ will be high as far as transport from the north is concerned during March 1949.

A similar argument would of course have to hold for advection from the south. It should be mentioned however that Karandikar [21] found no "definite correlation" at Delhi between ozone and temperature at 6 km. when all data were considered, but [15] during the season of western disturbances, "air of northerly origin in the upper part of the troposphere is accompanied by increase in ozone amount and advent of southerly air by a decrease." During the winter months, at least, one should expect $|r_5|$ to be high also at latitudes 29° N. If so, then the high value of $|r_5|$ at Washington and probably of $|r_1|$ can readily be explained by the "solid" advection which is observed.

$|r_1|$ *and* $|r_5|$ *low.*—Let us now apply the advection of figure 10a to July 1949. Since the advection is observed to be a "solid" current up to about 18–20 km. [17, 19, etc.], the previous argument will account for the observed relation between T_1 and T_5. But above 18 km. the observed winds are all easterly, and we have seen (figs. 3 and 4) that on any one day the east-west distribution of ozone is far from constant. Therefore below 18 km., the winds bring in high ozone from the north, corresponding say to high T_1. But above 18 km. where part of the ozone change occurs (fig. 10b, c), the ozone contribution may be either high or low and does not depend on T_1. Therefore more than one value of total ozone is to be expected for identical values of T_1. Obviously, then $|r_1|$ and also $|r_5|$ will be low.

From this discussion, it seems reasonable to expect on the basis of advection that even if ozone and temperature could be measured precisely enough, in certain months high values of $|r|$ are to be expected, while in other months, particularly during mid-summer, $|r|$ should be low.

VERTICAL MOTION

The second terms on the right of equations (2) and (3) express the temperature change and ozone change, respectively, due to vertical motion and require some discussion. There is general agreement that in the troposphere cold air advection, for example, is accompanied by sinking motion (fig. 10a); therefore advection is the more important factor in producing local cooling there since sinking produces warming. But for the stratosphere such general agreement is lacking. One school [7] believes that warm air advection is accompanied by rising motion as

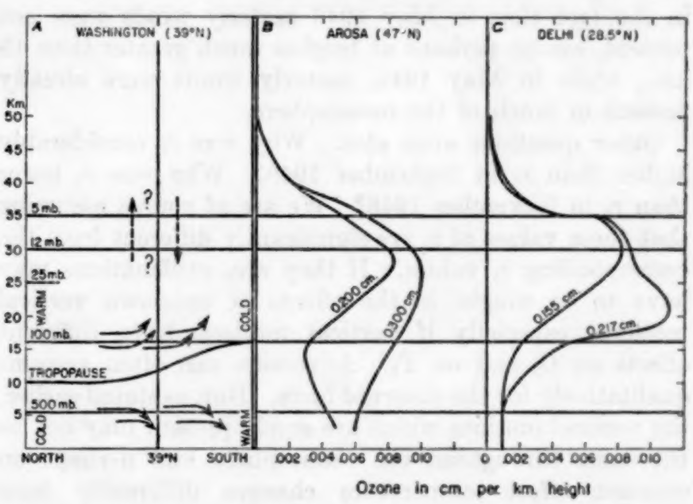

FIGURE 10.—(a) Schematic advection and vertical motion for north wind at Washington. (b) Vertical distribution of ozone at Arosa. (c) Vertical distribution of ozone at Delhi.

it is in the troposphere. Another school [16] believes that warm air advection in the stratosphere (stratospheric north winds at Washington) is accompanied by sinking motion. If on some occasion rising motion is present under such circumstances, then again advection is the predominant factor in changing T_1. But if sinking motion occurs, then *either* advection or vertical motion may be the more important factor.

Although the vertical motion near the 100-mb. level will affect T_1, ozone is changed only by vertical motions above about 25–30 km.; i. e., above the region of maximum ozone/km. (fig. 10). If ozone is lifted from the region below this critical height into the region above, some ozone is destroyed during the *rapid* return to photochemical equilibrium at the greater height [22]. Hence the total ozone in a vertical column is decreased. Likewise, if ozone is brought down from above about 30 km., the total ozone is increased. Vertical motions confined to the region below 25–30 km., by themselves do not change total ozone. In other words, vertical motion above 25 km. tends to change O_3 in the same sense that it changes temperature. But there is no a priori reason for supposing that the vertical motion near 100 mb. is the same as the vertical motion above 25–30 km. (above about 25 mb.).

In view of the uncertainty regarding the sign of V_z at the various heights in the ozonosphere, it is difficult to see what its contribution is to r_1 and r_5.

FURTHER DISCUSSION

Of course, the consideration of advection alone cannot explain all the features of figures 7 and 8. Why, for example, was r_5 high in May of 1948 and relatively low in May of 1949? Ordinarily direct balloon measurements show that easterly winds above 18 km. are already observed in May. But the "normal" 19-km. pressure chart for May [23] indicates northwesterly flow over Washington at that level. Perhaps then the answer lies in the fact that in May 1948 easterly winds were not present, except perhaps at heights much greater than 18 km., while in May 1949, easterly winds were already present in much of the ozonosphere.

Other questions arise also. Why was r_1 considerably higher than r_5 in September 1949? Why was r_1 lower than r_5 in November 1948? We are of course assuming that these values of r_1 are significantly different from the corresponding r_5 values. If they are, explanations may have to be sought in the effects of unknown vertical motions, especially if vertical motions have different effects on O_3 and on T_1. Advection can often account qualitatively for the observed facts. But, as stated earlier, the vertical motions which are surely present may not be the same throughout the ozonosphere and perhaps on occasion affect temperature changes differently from ozone changes. On these occasions, the unknown vertical motions will be reflected in r.

Also we have spoken of the air as moving "more or less" from one direction. While this is true, the speed of the winds is often quite variable with height [19]. For example, on a particular day, the wind may be practically calm near the 100-mb. level, but have velocities of more than 50 m. p. h. at heights below and above that level. Obviously the advective effect on temperature and on ozone will be quite different on such days. Such departures from the advection of an entire column of air from a single source region will also tend to reduce the value of r, if the argument given above is valid.

CONCLUSION

We have analyzed the total daily ozone measurements at Washington, D. C., have related the data to surface pressure systems, and have pointed out the similarities to and the differences from previous investigations. We have also correlated ozone with temperatures in the troposphere and stratosphere and have suggested that the existence or nonexistence of a "solid" air current is related to the high or low correlation coefficients, respectively.

It will be of interest now to examine the actual trajectories of the air at upper levels for the cases shown in figures 3–6, and to see to what extent the ozone departures can be explained by a simple "solid" advection hypothesis. For those cases in which this advection hypothesis fails, we should examine either the vertical velocity or the possibility of easterly winds above 18 km. These motions may in turn suggest mechanisms for surface pressure changes.

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AN OBJECTIVE METHOD OF FORECASTING SUMMER PRECIPITATION AT SALT LAKE CITY, UTAH

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ABSTRACT

An attempt is made to develop an objective method of forecasting summer precipitation at Salt Lake City, using moisture variables on a scatter diagram. These variables are surface dew point at Salt Lake City vs. the minimum temperature-dew-point spread between 700 and 500 mb. at a nearby raob station selected according to the 12,000-foot wind direction at Salt Lake City. Probability lines for the occurrence of both measurable rain and a trace or more are drawn. Skill scores and percentage of correct forecasts are computed for both original and test data and compared with Weather Bureau staff forecasts.

CONTENTS

INTRODUCTION

Forecasting the occurrence of summer precipitation in Utah, as well as in other dry climates, has often proved difficult, for rainfall is usually dependent on relatively narrow tongues of moisture protruding into the State from a southerly direction. Since several rather successful objective methods for forecasting precipitation at Pacific Coast stations and other points have been developed in the past few years, it was felt that a similar study undertaken for Salt Lake City might produce useful results.

Carpenter [1] used 700-mb. mixing ratios and relative humidities to forecast precipitation in Utah for all seasons. Most authors, as Brown [2], Vernon [3], Counts [4], and Jorgensen [5] have used rather extensive and elaborate typing systems in the development of their methods. Angell and Chen [6], on the other hand, in their report on forecasting rainfall at Los Angeles, reach the conclusion that a relatively simple forecasting system with a limited number of parameters yields results approximately equal to those of a highly complicated and time consuming typing system. Also, Price [7] obtained reasonably good results using a simple approach to forecasting thunderstorms at Washington. Therefore, since the time available for the study was somewhat limited, no attempt was made to undertake any extensive map typing, and the general procedure followed was to test the forecasting significance of numerous pertinent parameters by means of scatter diagrams.

At first the study was to include precipitation for all of the warm season, May through September. However, because it was quickly ascertained that July and August rainfall is generally of quite a different origin than May, June, and September precipitation, the field for consideration was narrowed to the midsummer months. In July and August, rainfall is usually associated with tongues of moist air moving into Utah from a southerly direction around the west side of a high-level anticyclone situated over the south-central portion of the United States. In May, June, and September, however, in addition to the above, precipitation also accompanies frontal activity and cold Lows aloft. Very few significant fronts pass Salt Lake City from the west or northwest in midsummer, and most of these are "dry" fronts accompanied by little or no rain. Cold Lows aloft over or near northern Utah during the midsummer period under study were practically nonexistent. Thus, the relatively uncomplicated synoptic situations associated with midsummer rainfall at Salt Lake City were found to lend themselves fairly well to the application of objective forecasting techniques.

DATA

Data for July and August 1946 through 1949, as well as Weather Bureau Provisional Forecast Rating forms for checking accuracy of results against the Salt Lake City official staff forecasts, were available for the study. Use of earlier data was precluded by the absence of Las Vegas radiosonde observations, which were not begun until September 1945. Records for 5 of the available 8 months were used for the original data, and records for 3 months—July 1946, August 1948, and July 1949—were set aside for test data. The data were so divided that wet and dry months were represented in each sample and at least one July and one August was reserved for the test sample.

The period 1130 MST to 0530 MST the following day was chosen as the forecast period for the following reasons: (1) Most telephone calls to the Weather Bureau for

weather information are received in the morning, and the question most frequently asked is, "Will it rain today or tonight?" (2) The morning forecast gets the best distribution to newspapers, radio stations, and wire service news agencies. (3) Most summer precipitation falls in the afternoon or evening, with very little falling during the six-hour period from 0530 to 1130 MST.

The latest available data for the forecast are the 0530 MST surface weather map, the 0230 MST pibal chart and the 2030 MST previous evening raobs and upper air charts. In actual practice the forecast can be made as soon as the 0530 MST synoptic report for Salt Lake City is available.

VARIABLES

Numerous variables that were believed to be significant in forecasting rainfall at Salt Lake City were tested. These are listed below:

A. Circulation variables:
   - Sea level pressure at Salt Lake City.
   - 850-mb. height at Salt Lake City.
   - 10,000-, 12,000-, and 14,000-foot winds at Ely, Las Vegas, and Salt Lake City.
   - 700- and 500-mb. contour flow.
   - 700- and 500-mb. heights and height differences at Ely and Las Vegas.

B. Moisture variables:
   - Surface dew point at Salt Lake City.
   - Surface wet-bulb temperature at Salt Lake City.
   - 700- and 500-mb. dew point at Las Vegas, Ely, Grand Junction, Boise, and Lander.
   - Minimum temperature-dew point spread between 700- and 500-mb. at Las Vegas, Ely, Boise, Lander, and Grand Junction.

C. Stability variables:
   - 700- and 500-mb. temperatures at Las Vegas and Ely.
   - Temperature difference, 700–500-mb., at Las Vegas and Ely.

In addition, 3-hourly surface pressure tendencies at Salt Lake City were tested.

Of all these, the moisture variables played by far the dominating role, with circulation next in importance. Stability appeared to play a less important role; in fact, the air over the Plateau in midsummer is nearly always conditionally and frequently convectively unstable. The 3-hourly surface pressure tendency at Salt Lake City proved to be of no value because precipitation was usually not associated with moving troughs or fronts.

In the final selection of moisture variables, one parameter was chosen to indicate moisture already present at Salt Lake City, and another to indicate whether moist or dry air would move into the area during the forecast period. As indicators of moisture already present, the 0530 MST dew-point and wet-bulb temperatures both showed good correlation with the occurrence or nonoccurrence of precipitation. The dew point was selected because it correlated slightly better than the wet-bulb temperature, had a wider range, and appears in the regular synoptic report. Table 1 shows the frequency distribution of rainfall occurrence with the Salt Lake City dew point.

TABLE 1.—*Frequency of occurrence of measurable rainfall and trace or more with the 0530 MST dew point at Salt Lake City*

Salt Lake City 0530 MST dew point (° F.)	Total cases	Cases with 0.01 inch or more	Percentage frequency	Cases with trace or more	Percentage frequency
61–65	4	4	100	4	100
56–60	8	5	62	8	100
51–55	33	10	30	24	73
46–50	37	5	14	14	38
41–45	28	1	4	7	25
36–40	30	0	0	2	7
30–35	15	0	0	1	7
Total	155	25	----------	60	----------

As an indicator of the moisture content of the air that would move into the area during the forecast period, the 2030 MST, minimum spread between temperature and dew point in the layer from 700 to 500 mb. at one of the various raob stations surrounding Salt Lake City, selected according to the 12,000-foot wind direction at Salt Lake City at 0230 MST, was used. After numerous trials the following raob stations were used for the various wind directions:

Direction	Station
S-SSW	Las Vegas
SW	Las Vegas and Ely*
W-WSW	Ely
WNW-NNW	Boise
N-ENE	Lander
E-SSE	Grand Junction

*Use arithmetic mean of the minimum spreads at these stations.

Actually there were no cases of measurable rain with WNW to NNW winds, as only relatively dry air moved in from the northwesterly quadrant. The wind direction was between N through E to SSE in only 8 cases out of 155, so the Lander and Grand Junction raobs were seldom used. The raob for Ely or Las Vegas was used for 133 out of the 155 cases.

The average height of the layer of maximum moisture was about 550 mb. (16,000 feet), suggesting that a better selection of the raob station might be made by using the wind for a level higher than 12,000 feet. However, winds at levels higher than 12,000 feet were missing too frequently to be of use in an objective forecasting method. In the few cases where the 12,000-foot wind was missing, the direction was estimated from streamlines at 12,000 feet drawn on the pibal chart.

An attempt was made to use the direction of the 700- and 500-mb. contour lines through Salt Lake City to indicate air flow, and thus which raob to select for moisture value. The attempt had to be abandoned because

the height field over the Plateau in summer is fairly flat and the drawing of the contours is anything but objective. Also, the 0230 MST pibal has a decided advantage in being for a time 6 hours later than the time of the constant pressure charts.

The minimum temperature-dew-point spread in the 700- to 500-mb. layer correlated better with the occurrence of measurable rainfall than the average moisture value for the layer. This is probably because the moist tongue of air is usually of quite shallow depth when it first appears on the sounding, and frequently an average moisture value will not show a significant rise until too late to be of forecast value. Since the sounding used is 24 hours before the midpoint of the forecast period, the first indication of an increase in moisture is highly important. The use of 700- and 500-mb. dew points as indicators of moisture also proved inferior, because frequently the moist layer first appeared somewhere between these two constant pressure surfaces.

Table 2 shows the frequency distribution of rainfall occurrence with the minimum temperature-dew-point spread at any level between 700 and 500 mb. at the selected raob stations. Elevated surfaces other than 700 and 500 mb. gave poorer results. A comparison of table 2 with table 1 indicates the surface dew point to be the more significant variable for forecasting the occurrence of rainfall.

TABLE 2.—*Frequency of occurrence of measurable rainfall and trace or more with minimum temperature-dew-point spread in the 700- to 500-mb. layer at Las Vegas, Ely, Boise, Lander, or Grand Junction, selected according to the 12,000-foot wind direction at Salt Lake City.*

Minimum temperature-dew-point spread (°F.)	Total cases	0.01 inch or more	Percentage frequency	Trace or more	Percentage frequency
0–2	23	8	35	15	65
2½–5	41	11	27	25	61
5½–8	25	4	16	13	52
8½–11	15	1	7	2	13
11½–14	15	0	0	2	13
14½–17	10	1	10	2	20
17½–20 or more	26	0	0	1	4
Totals	155	25		60	

SCATTER DIAGRAMS

The scatter diagram used in making the forecast is shown in figure 1. As abscissa, it has the minimum temperature-dew-point spread in the 700- to 500-mb. layer at 2030 MST at Las Vegas, Ely, Boise, Lander, or Grand Junction, selected according to the 12,000-foot wind direction at 0230 MST at Salt Lake City; and as ordinate, the 0530 MST Salt Lake City surface dew point. For each day a plotted symbol indicates occurrence of no rain, a trace, a "dry" thunderstorm, or 0.01 inch or more precipitation during the 18-hour period 1130 MST to 0530 MST the following day. "Dry" thunderstorms (thunder heard but no rainfall reported at observing point) were included because frequently in these cases rain is observed to be reaching the ground in the immediate vicinity of the station. The line of best separation between measurable and nonmeasurable rain cases was drawn on the diagram by eye and its correctness of position checked by use of the skill score. (See Angell and Chen [6], for example.)

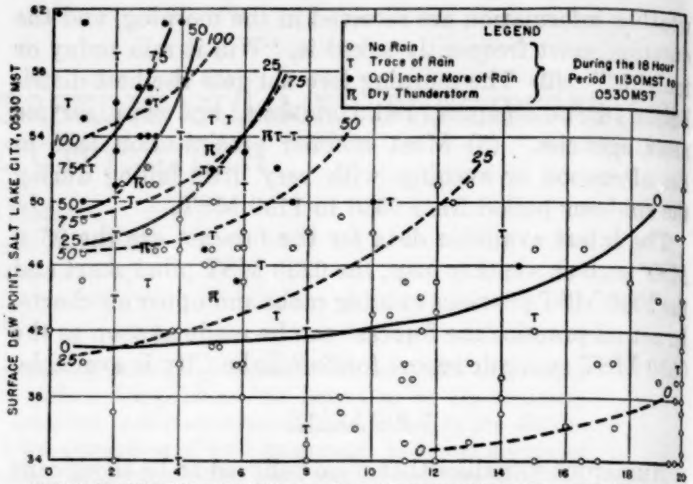

FIGURE 1.—Scatter diagram showing isolines of probability (percent) of measurable rainfall (solid lines) and of trace or more, including dry thunderstorms (dashed lines) at Salt Lake City for 18-hour period 1130 MST to 0530 MST the following day, during the months of July and August. See text, p. 149, for explanation of selection of raob station to be used in determining an abscissa value.

The maximum skill line was used as the 50 percent probability line, and 25 percent and 75 percent probability lines for the occurrence of measurable rainfall were also computed and drawn (solid lines). In addition, probability lines for a trace or more, including "dry" thunderstorms were drawn (dashed lines). These lines were computed in the following manner: The diagram was divided into boxes with an approximately equal number of points, and the percentage of observations with a trace or more of rain, and with 0.01 inch or more was computed for each box. Isolines were then drawn to fit the data, with a minimum of smoothing.

In an attempt to improve the forecasting skill of the method, a mean 700-mb. chart for 2030 MST on days preceding measurable rain cases at Salt Lake City was prepared and compared with a sample mean chart for the evening preceding no-rain days. A chart of height differences between the two mean charts was prepared (fig. 2), after the manner of Angell and Chen [6]. On the mean rainy-day chart, heights over the Pacific Northwest were much lower than on the mean no-rain chart. Also on the mean rainy-day chart, there was an east-southeasterly flow from the Gulf of Mexico into the southern Plateau, whereas on the mean no-rain map this moist air current was replaced by a northerly circulation over the west Gulf region, the mean position of the high-level anticyclone being shifted considerably westward. This latter feature is in fairly good agreement with Reed's observation [8] that when the high-level anticyclone is located west of

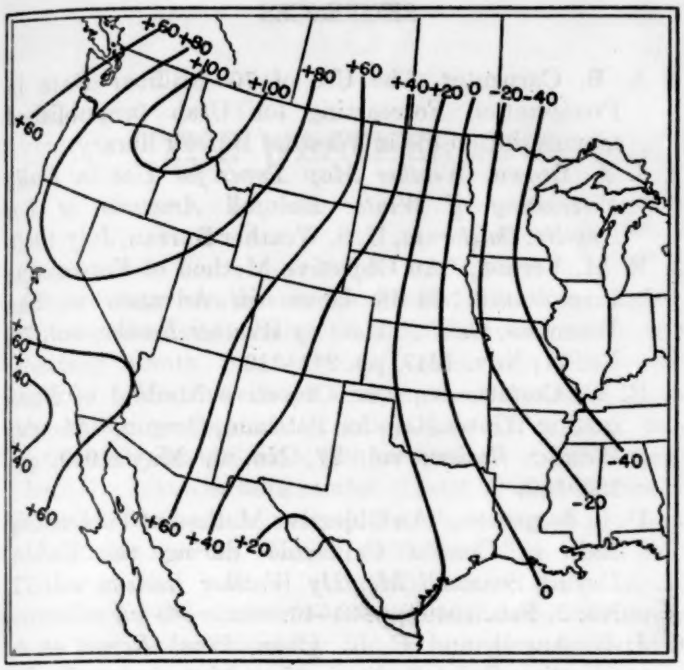

FIGURE 2.—Chart showing height differences (ft.) between mean 700-mb. no-rain chart and mean 700-mb. rain chart (no-rain chart minus rain chart).

the Continental Divide the southwest desert area is dry, but when to the east of the Divide, showers occur.

To make use of the centers of maximum difference between the two mean charts, a scatter diagram (not shown) was constructed using the 700-mb. height at Phoenix versus the height difference Spokane minus St. Cloud. Probability lines for the occurrence of measurable rain were drawn and this chart was then combined with figure 1 into a joint probability chart. However, this latter chart did not produce any higher forecasting skill scores on either the original or test data than figure 1 alone, so the latter was used as the final forecasting diagram. The lack of improvement in skill is probably because of the high degree of relationship between the differences in flow pattern of the two mean charts and the amount of moisture present at the southern Plateau raob stations. Either of these criteria alone shows considerable forecasting skill but the two apparently cannot be combined to increase the skill.

RESULTS FROM ORIGINAL DATA

Using the 50 percent probability line as the dividing line for the forecasting of occurrence or non-occurrence of measurable precipitation from the scatter diagram (fig. 1), results from original data are compared in table 3 with Weather Bureau staff forecasts recorded on Provional Forecast Rating forms. From this contingency table, skill scores and percentages of hits were computed. It may be seen that the skill score for the objective method was slightly higher than the score for the staff forecasts.

908625—50——2

TABLE 3.—*Contingency table for original data, showing comparison of objective forecasts with Weather Bureau staff forecasts*

		Objective forecast			Staff forecast		
		Rain	No-rain	Total	Rain	No-rain	Total
Observed	Rain	17	8	25	13	12	25
	No-rain	6	124	130	3	127	130
	Total	23	132	155	16	139	155

Objective method: Skill score 0.66; percentage hits 91.
Staff forecasts: Skill score 0.58; percentage hits 90.

A few of the measurable rain cases fell well outside the 25 percent probability line on the scatter diagram. These were investigated individually. Most of the errors were caused by moist air at fairly high levels (about 16,000 feet) moving so rapidly from the south into the Salt Lake area that this moisture was not in evidence at any of the immediately surrounding raob stations at 2030 MST the previous evening. This type of failure is due mainly to the large time lag between the latest available upper air data and the time of making the forecast.

There were a few cases where the probability of precipitation was fairly high yet no measurable rain occurred. In some of these failures, a trough passed Salt Lake City shortly after 0230 MST, bringing in drier air from the northwest. If the trough should pass before the forecast is issued at 0900 MST, the forecaster can, of course, subjectively improve the objective forecast by taking this factor into consideration.

RESULTS FROM TEST DATA

Skill scores and percentages of hits were also computed for the three months of test data from the contingency table shown as table 4.

TABLE 4.—*Contingency table for test data, showing comparison of objective forecasts with Weather Bureau staff forecasts*

		Objective forecast			Staff forecast		
		Rain	No-rain	Total	Rain	No-rain	Total
Observed	Rain	6	6	12	8	4	12
	No-rain	5	76	81	6	75	81
	Total	11	82	93	14	79	93

Objective method: Skill score 0.45; percentage hits 88.
Staff forecasts: Skill score 0.55; percentage hits 89.

The skill score of the objective method falls somewhat below staff results. This is possibly due to the limited data available in computing the original line of maximum skill. With more years of data available, the skill scores of the original and test data would probably tend to approach each other more closely.

CONCLUSIONS

The objective method of forecasting midsummer precipitation at Salt Lake City compares favorably with Weather Bureau staff results in both skill scores and percentage hits. Undoubtedly there are some pertinent variables which have not been tested, particularly stability parameters, and it is possible that higher skill may yet be obtained by graphically combining scatter diagrams of these yet untried variables with those already tested.

In actual use, the scatter diagram may be helpful in a way not yet mentioned. The probability lines for a trace or more were added to the scatter diagram because it was believed that they would prove useful in forecasting very light or scattered showers, or showers over the nearby mountains, when the probability of a trace or more was 50 percent or greater, but the probability was less than 50 percent for measurable rainfall. On the other hand, when the probability of measurable precipitation was 50 percent or more, the forecast could then simply indicate showers, or possibly moderate to heavy showers. In its present form, the method is simple, quick to use, and almost completely objective. As already indicated, subjective improvements may be made by the forecaster under certain conditions.

ACKNOWLEDGMENTS

Appreciation is expressed for several helpful suggestions received from J. C. Thompson, Weather Bureau research forecaster at Los Angeles, and from Weather Bureau forecasters at Salt Lake City.

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THE WEATHER AND CIRCULATION OF AUGUST 1950 [1]

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The average weather in the United States in August 1950 was basically similar to that observed during the preceding month (see July 1950 MONTHLY WEATHER REVIEW). Monthly mean temperatures during August were again predominantly below normal east of the Continental Divide and above normal to the west (Chart I). Likewise both rainfall (Chart V) and cloudiness (Chart IV) were excessive in southern and central portions of the Plains and the Mississippi Valley. The recurrence of this weather pattern was reflected in the seasonal anomalies for the summer of 1950, reproduced in figure 1. These are characterized by below normal temperatures and above normal rainfall in most of the eastern two-thirds of the country, and above normal temperatures and below normal rainfall in most of the western third of the Nation. On the whole this summer was probably the coolest and rainiest since 1915 in the United States east of the Continental Divide. In portions of the Great Lakes region the temperature did not exceed 90° F. all summer, and 1950 was reminiscent of the famous "year without a summer".

Marked persistence of the weather anomalies in the United States was accompanied by an equally striking persistence of the basic circulation patterns. Thus during August, as in July, a mean trough in the constant pressure surfaces was located in eastern North America at all levels of the troposphere from 700 mb. to 300 mb. (Charts IX to XI), while a mean ridge was present in the western part of the continent, roughly along the Continental Divide. 700-mb. heights were below normal [2] throughout the length of the trough, from Baffin Bay to the Gulf of Mexico, and above normal throughout the ridge, from Alaska to Mexico (fig. 2). As a result mean geostrophic air flow at 700 mb. was almost due northerly relative to normal throughout central North America, and repeated invasions of cool Canadian air penetrated southward into central and eastern United States. These polar outbreaks accompanied the movement of a relatively large number of anticyclones from central and western Canada into the northern and central Plains and the Lakes region along tracks shown in Chart II. Rapid warming of the polar air by insolation in central and eastern United States was probably prevented by frequent frontal passages and by large amounts of cloudiness in the vicinity of the trough aloft. Thus, comparison of figure 2 with Charts I, IV, and V (inset), reveals that during August, as in July, there was generally good agreement between the areas of cyclonic curvature and negative height anomaly at

[1] See Charts I-XI, following p. 160, for analyzed climatological data for the month.

[2] The 700-mb. height anomalies for August 1950 were computed from revised normals now being prepared in the Extended Forecast Section. These revised normals will be used for all subsequent articles in this series.

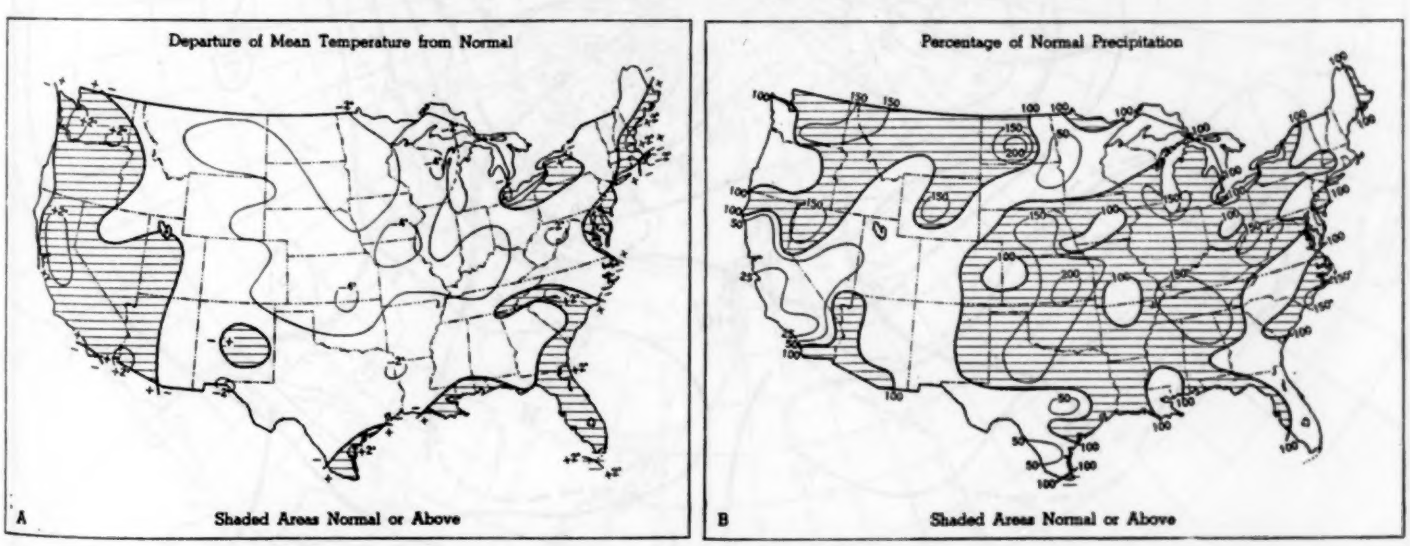

FIGURE 1.—Charts showing average temperature and precipitation anomalies for the summer of 1950 (June through August). Temperature departure from normal is shown in degrees Fahrenheit. (Based on preliminary telegraphic reports. From the "Weekly Weather and Crop Bulletin" for the week ending September 12, 1950.)

700 mb. and the regions of much cloudiness, sub-normal temperature, and above-normal rainfall at the surface.

The principal difference between the mean 700-mb. map for August and that for July in the vicinity of North America was the presence of a weak trough off the East Coast, from Nantucket south to the Bahamas, during August (fig. 2). The extremely short wavelength between this trough and the full latitude trough in eastern North America is difficult to rationalize, but it may be due to the fact that the Atlantic trough is mainly a low latitude feature of the circulation with 700-mb. flow from an easterly direction relative to normal throughout its length. An interesting parallelism may be noted between the two trough lines and the tracks of two tropical hurricanes (Chart III) one up the eastern Mississippi Valley and the other off the East Coast. Between the two troughs a weak but distinct 700-mb. ridge extended from a high center in Florida northward to Lake Erie. Anticyclonic curvature in this ridge was primarily responsible for deficient rainfall (Chart V inset) and slightly above normal temperatures (Chart I) in portions of the East Coast States. These conditions were also favored by the presence of a monthly mean 1018-mb. High centered in West Virginia at sea level (Chart VI). Easterly winds south of this High were stronger than normal (Chart II inset). They transported relatively cool maritime air from the Atlantic and were probably responsible for below normal temperatures in eastern Florida and South Carolina (Chart I).

The 700-mb. ridge in the western part of the United States was better developed in August than in July. In this region heights were well above normal and anticyclonic curvature was pronounced at 700 mb. (fig. 2). Correspondingly, surface temperatures were above normal (Chart I), sunshine abundant (Chart IV), and rainfall deficient (Chart V inset) in practically all areas from the Continental Divide to the Pacific Ocean. Temperatures averaged more than 2° above normal and there was no measurable precipitation in parts of Washington, Utah, Nevada, California, and Arizona (Chart V). These conditions culminated on September 1 in an all-time nationwide September heat record of 124° at Yuma, Ariz. and were accompanied by extensive forest fires in California.

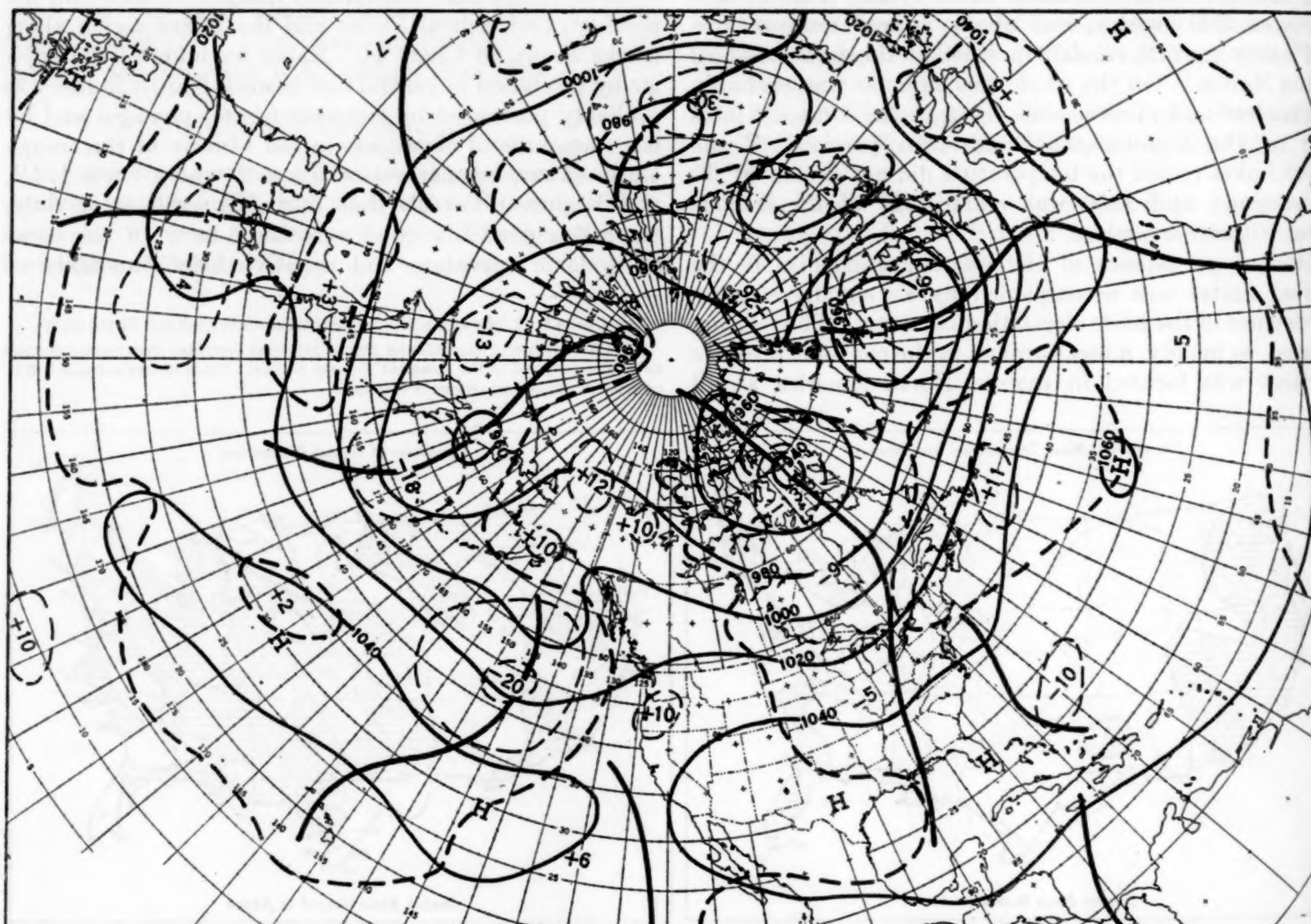

FIGURE 2.—Mean 700-mb. chart for the 30-day period August 1–30, 1950 inclusive. Contours at 200-foot intervals are shown by solid lines, 700-mb. height departure from normal (based on revised normals being prepared by Extended Forecast Section) at 100-foot intervals by dashed lines with the zero isopleth heavier. Anomaly centers are labeled in tens of feet. Minimum latitude trough locations are shown by heavy solid lines.

Hot dry weather in the Far West was also reflected in a well-developed thermal trough at sea level (Chart VI), and it accentuated the normally strong thermal gradient between coastal and interior California. Consequently strong sea breezes, as indicated by the Los Angeles wind rose, produced below normal temperatures along the coast of southern California (Chart I).

Along practically the entire Gulf Coast temperatures were above normal (Chart I), skies were clear more than half the time (Chart IV), and rainfall was deficient (Chart V inset) during August. These weather anomalies were associated with a flow of relatively dry air from a northerly direction both at 700 mb., where winds were more northwesterly than normal (fig. 2), and at sea level, where winds were from a northeasterly direction relative tc normal (Chart II inset). This circulation cut off the normal source of moisture and weakened the prevailing cool sea breeze from the Gulf of Mexico. In addition an east-west ridge line extended along the Gulf Coast at 700 mb. and probably suppressed convective activity. Chart I shows a sharp dividing line through central portions of Texas, Louisiana, Mississippi, Alabama, and Georgia between below normal temperatures to the north and above normal temperatures to the south. This boundary coincided with a slow moving polar front on many individual weather maps during August but it is not well delineated on the monthly mean pressure maps.

Rainfall was deficient in most of the Northern Plains and Great Lakes regions (Chart V inset) despite the presence of cyclonic curvature and negative height anomalies at 700 mb. (fig. 2). This may be attributed to the prevalence of anticyclonic conditions at sea level, as attested by the large number of migratory Highs which traversed the region (Chart II), the existence of anticyclonic curvature in the monthly mean sea level isobars (Chart VI), and the fact that monthly mean pressure at sea level was generally above normal (Chart II inset). On the other hand, in southern and central parts of the Plains and Mississippi Valley, where rainfall exceeded the normal by more than 2 inches, cyclonic conditions aloft were complemented by cyclonic curvature in the mean sea level isobars (Chart VI). Contributing factors to the excess precipitation in the western Plains were upslope action, indicated by southeasterly flow relative to normal, (Chart II inset), and the presence of a quasi-stationary frontal zone along the Divide during many days of the month.

In conclusion, it is noteworthy that marked persistence of the basic circulation pattern from July to August 1950 was evident in most of the Northern Hemisphere as well as in the United States. Comparison of figure 2 for August with figure 1 of the article on the July weather and circulation in the MONTHLY WEATHER REVIEW shows that during both months the Icelandic Low was southeast of its normal position, the Azores High was displaced to the northwest, a strong blocking type ridge was located over Scandinavia, and a deep trough ran along the Ural mountains. The eastern cell of the Pacific High however, was much weaker and farther south in August than in July. 700-mb. heights were below normal in most of the eastern Pacific in August, and a deep polar trough extended from the Gulf of Alaska southward to 30° N., 155° W., where it joined a well-developed easterly wave over the Hawaiian Islands. This circulation pattern was associated with generally heavy rainfall over the Hawaiian Islands, where a true hurricane made one of its rare appearances in mid-August.

908625—50——3

AN UNUSUAL SURGE OF COLD AIR ACROSS THE NORTHWEST UNITED STATES ON AUGUST 22 AND 23, 1950

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INTRODUCTION

One of the few marked weather changes which occurred in the United States during the relatively inactive month of August 1950 was the sharp drop in temperatures which took place in the northwestern States on August 22 and 23. For example, on August 22 the maximum temperature at Boise, Idaho was 101° F. while on August 23 the maximum at this station reached only 73° F. Figure 1 shows the sharp decreases in maxima which occurred throughout Washington and Oregon with the influx of cold air. Note that in the area just west of the Cascades 24-hour decreases of between 10 and 25 degrees occurred. Cooler weather for the area in which the most marked cooling took place was correctly predicted as early as the forecast made from the 0530 MST map of August 21. No cooling for the area east of the Cascades was forecast from the 0530 MST map of August 21, however.

Figure 2 shows the result of the continued eastward advection of the unusually cold air with cooler temperatures occurring throughout most of Washington and Oregon and eastward beyond the Continental Divide. Cooling which occurred east of the Divide was due, in a large measure at least, to a southward surge of Polar Continental air.

The continued advection of the cold air eastward across the Cascades was not anticipated. For example, no cooling was forecast for Idaho, eastern Washington, or western Montana from the 0530 MST map of August 22, and the 30-hour prognostic charts made from the 2330 MST map of August 21, and from the 1130 MST map of August 22 issued by the WBAN Analysis Center indicate no cold front moving in from the west. The fact that these latter changes were not anticipated by synoptic meteorologists and forecasters indicates that this synoptic situation and its antecedents were sufficiently unusual to justify a review.

SOURCE OF THE COLD AIR

In looking for the source of the cold air the twice-daily radiosonde observations from the stationary weather ship

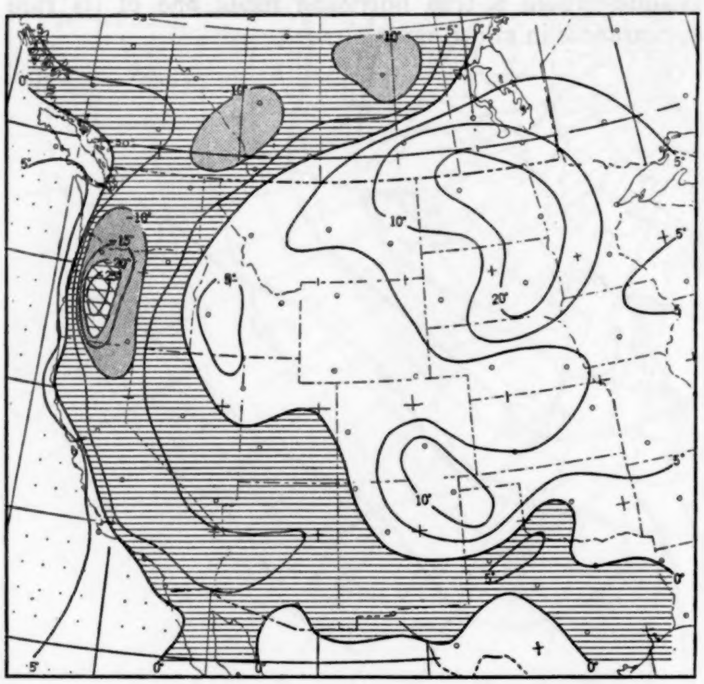

FIGURE 1.—Change of maximum temperature from August 21 to August 22, 1950.

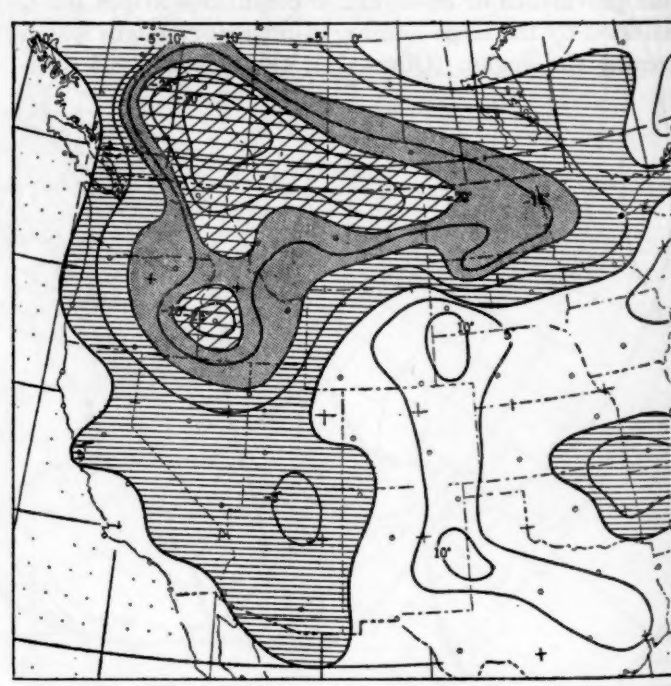

FIGURE 2.—Change of maximum temperature from August 22 to August 23, 1950.

at 50° N., 145° W. were first examined. No significant cooling is shown in these soundings until 2000 MST August 22 at which time the cold air in which we are interested had already moved inland. The cold air, therefore, did not follow a normal track from the west-northwest to the Pacific Coast.

Naturally, temperature changes aloft paralleled the changes in surface temperatures. During the 24-hour period, ending at 0800 MST August 23, cooling at 700 mb. of 9.0° C. was reported at Boise, Idaho, and 7.4° C. at Spokane, Wash. This suggested tracing the trajectory of the cold air at 700 mb. By tracing each 12-hour segment of the trajectory along the appropriate 700-mb. contour shown on the WBAN Analysis Center charts, it was possible to trace the cold air back to the cold core of a Low that had become stagnant over the Pacific at 46° N., 141° W. This Low had remained inactive and nearly stationary since its formation on August 8. Therefore, in the absence of a dense network of surface and upper air ship reporting stations off the west coast, satisfactory forecasting of the cold outbreak depended upon discovering the mechanism which changed the circulation pattern in such a way that the cold air was advected eastward.

TRAJECTORY OF THE COLD AIR

It was at first presumed that the change in the low level circulation pattern was due to some marked change in the upper air pattern which preceded the surface change or which, at least, could have been foreseen in time to forecast the cold outbreak. However, investigation of the charts drawn in the WBAN Analysis Center shows no marked changes in the circulation which could have been used for this purpose.

The possibility that a fresh surge of cold air from the west disturbed the stationary condition within the cold Low was next investigated. Charts for the week preceding August 20, the date on which the cold air south of the stationary Low began to move eastward, were reexamined. Special attention was given to conditions at 700 mb. At 2000 MST August 16, a reconnaissance plane at 700 mb. reported an abrupt rise in temperature of about 5° C. and an accompanying wind shift during flight from about 52° N., 165° E. to 45° N., 150° E. This suggests that the flight passed through a front. On the chart for the time of this flight, Attu, Alaska, reported a temperature of −6.5° C. at 700 mb. This was in contrast to the last previously reported value of −1.8° C. at 2000 MST August 14.

Upon this evidence a cold front was introduced on the chart for the 17th from a point just east of Attu, thence south-southwestward, then westward along the 48th parallel, and finally west-northwestward passing just south of Kamchatka (see fig. 3). After extrapolating this front westward at the speed of the appropriate geostrophic winds, it was found that it explained certain temperature changes which had been noted over Kamchatka during

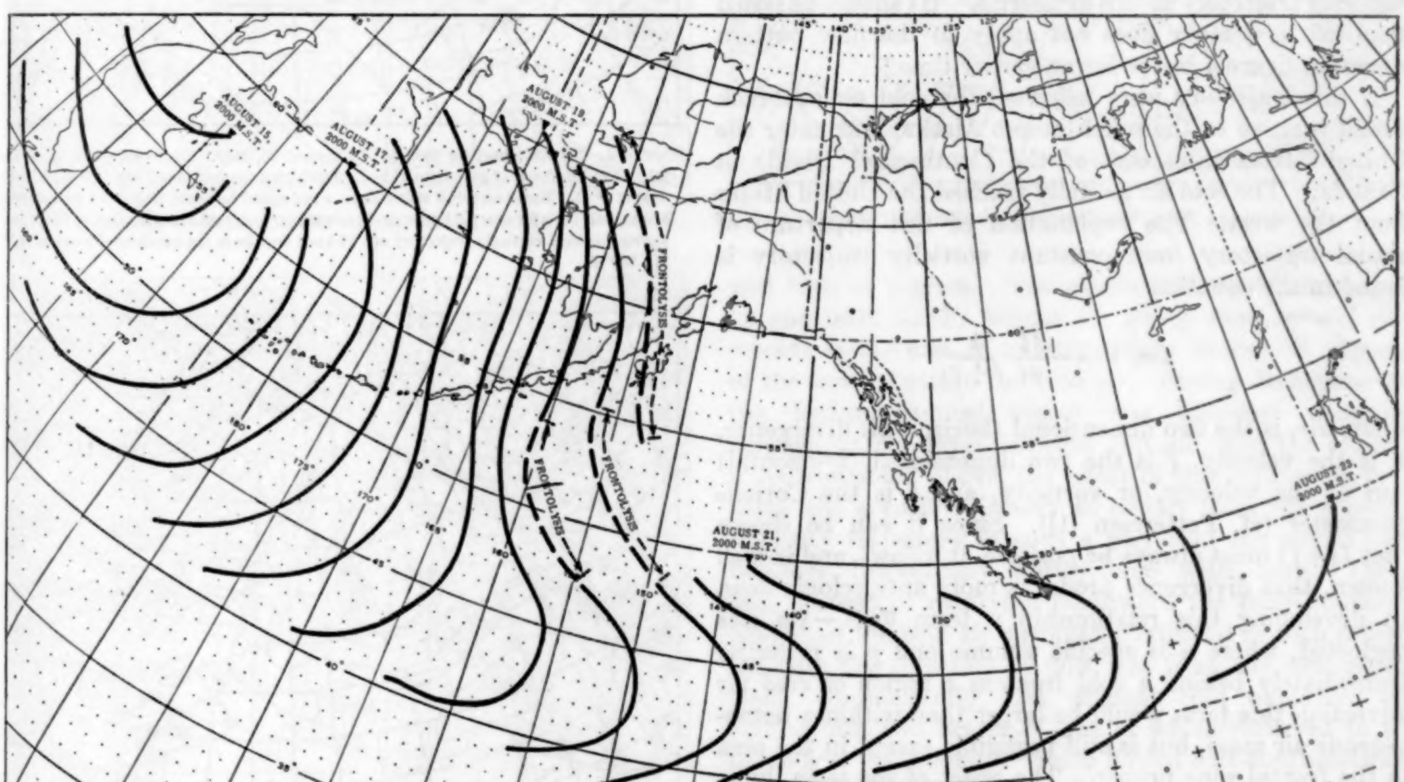

FIGURE 3.—Successive positions, at 12-hour intervals, of the cold front at the 700-mb. level.

the preceding 48 hours. Furthermore, when the cold front was moved eastward with the approximate speed of the geostrophic winds, its passage at Adak, Alaska, coincided very well with the drop of the 700-mb. temperature from +0.5° C. at 2000 MST August 17 to −5.5° C. at 0800 MST August 18. Similarly, the passage at St. Paul Island checked well with the change in temperature at the 700-mb. level from −1.2° C. at 0800 MST August 18 to −5.5° C. at 0800 MST August 19. This evidence establishes the existence of a cold outbreak which came originally from the north-northwest. Furthermore, extrapolating eastward with the instantaneous geostrophic flow in the cold air behind several segments of the front, one obtains a frontal position as shown in figure 3 for the time 2000 MST, August 18.

At this point it seems appropriate to investigate the constant vorticity trajectory of the air behind this cold air outbreak. Because very few reports were available in the area where the cold air first appeared, it is not possible to determine the exact speed and direction of movement of the cold air, and to fix exactly the inflection point used in computing the trajectory. However, based on data available, it appears that the cold air surge came from a north-northwesterly direction at approximately 30 k. and the center of the surge (and therefore the region of minimum shear) was about long. 160° E. The flow was further assumed to be straight at 52.5° N., 160° E. Using the initial conditions specified above, one obtains the constant vorticity trajectory shown in figure 4. (It should be noted that this trajectory does not apply to the flow pattern shown in figure 4 but is for an earlier time.)

If this trajectory were followed, the cold air outbreak would recurve to the north across Alaska, and enter the United States from east of the Continental Divide in Canada. The cold air actually reached the United States from the west. The explanation of this departure of actual trajectory from constant vorticity trajectory is found in the equation

$$div_2\, V = -\frac{d\zeta}{dt}\frac{1}{f+\zeta}$$

where div_2 is the two dimensional (horizontal) divergence, V is the velocity, ζ is the two dimensional (horizontal) curl of the velocity, or vorticity, and f is the Coriolis parameter (cf. Petterssen [1]). Since it can be shown that $(f+\zeta)$ must always be positive, it follows, and is well known, that divergence produces more anticyclonic flow. In developing this relationship a term $\nabla\alpha \times -\nabla p$ was neglected, where α is specific volume and p is pressure. Immediately behind a cold front in a region of cold air advection this term would be larger than within a homogeneous air mass, but is still negligible except in the area in the frontal zone proper. The effect of the term, however small, in the region of cold air advection would work in opposition to the effect of divergence.

It should also be mentioned that the vorticity may be expressed as two components; viz., a term involving shear and a term involving instantaneous curvature of the flow. The discussion that follows applies to one or more streams of air, within which the velocity reaches a maximum near the center at which point the velocity gradient vanishes. Thus in dealing with the center of such streams only the curvature term of the vorticity is considered.

As was originally pointed out by Ryd [2, 3] and has more recently been emphasized by Scherhag [4] and Wobus [5] directional divergence in the isobaric (or contour) field produces divergence in the flow. Examination of figure 4 and of 700-mb. charts preceding this (not shown) shows marked divergence of the contours at this level within the cold air behind the cold front. A similar pattern existed in the surface analyses for the 18th

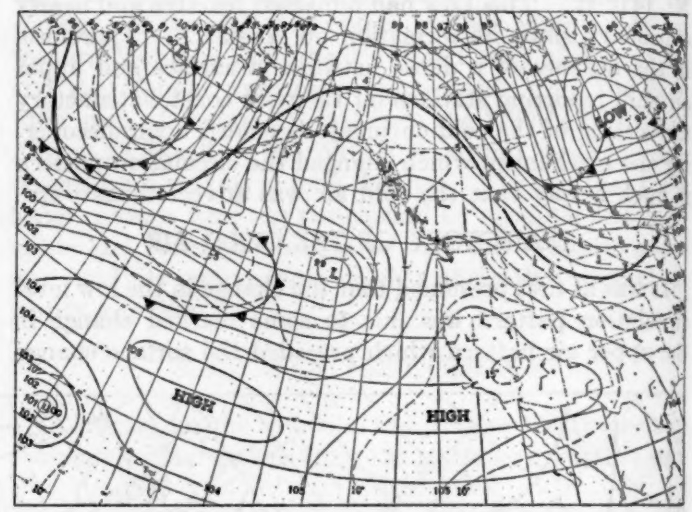

FIGURE 4.—700-mb. chart for 0800 MST, August 20, 1950. Contours (solid lines) are labeled in hundreds of geopotential feet. Isotherms (dashed lines) are drawn for intervals of 5° C. Barbs on wind shafts show wind speed in knots (full barb for every 10 knots, half barb for every 5 knots, and pennant for every 50 knots). Heavy black line shows constant vorticity trajectory of a 30-knot flow from the north-northwest at 52.5° N., 160° E.

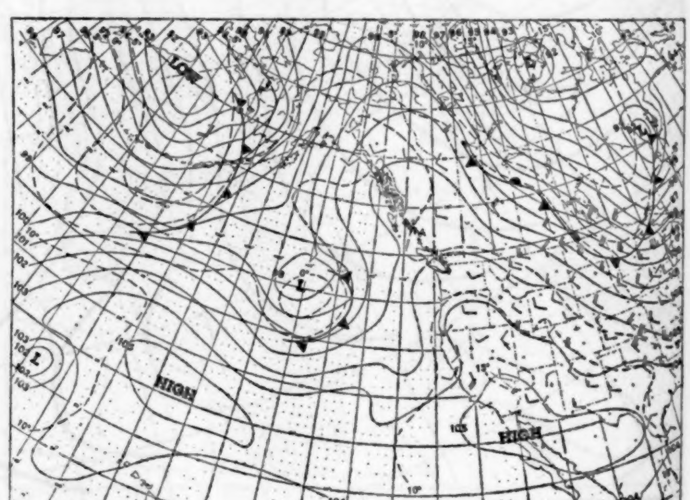

FIGURE 5.—700-mb. chart for 0800 MST, August 21, 1950.

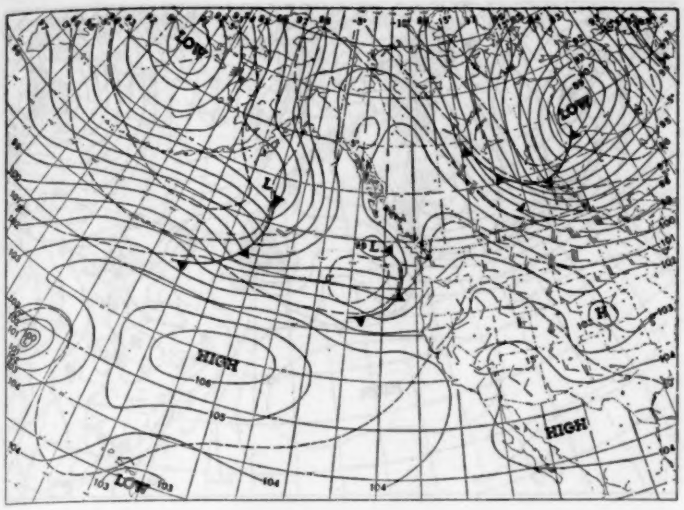

Figure 6.—700-mb. chart for 0800 MST, August 22, 1950.

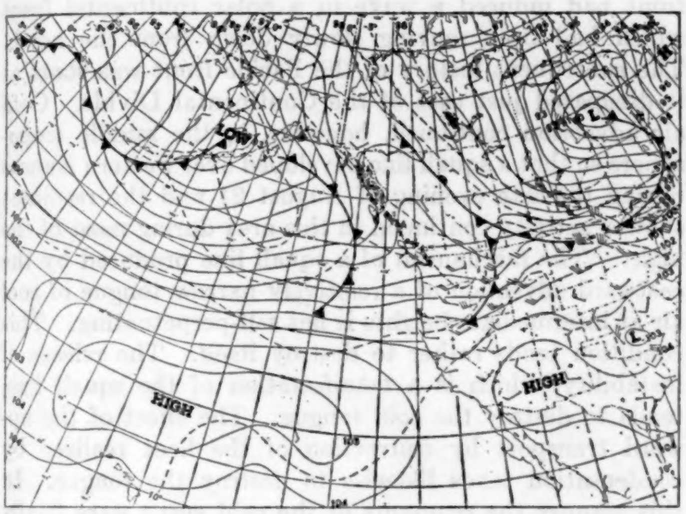

Figure 7.—700-mb. chart for 0800 MST, August 23, 1950.

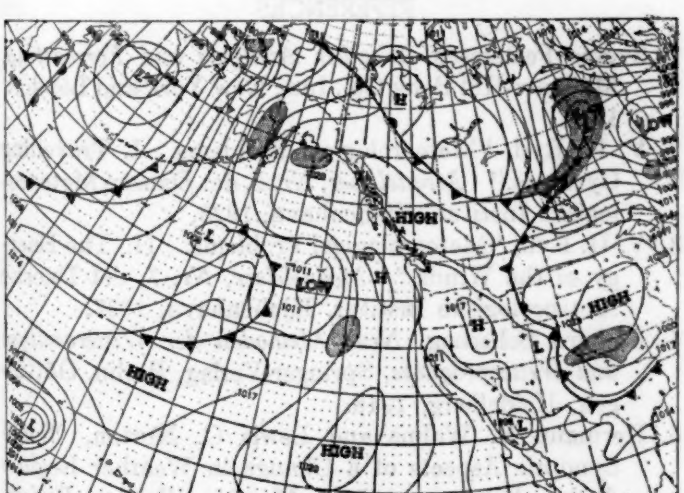

Figure 8.—Surface weather map for 0530 MST, August 20, 1950. Shading indicates areas of active precipitation.

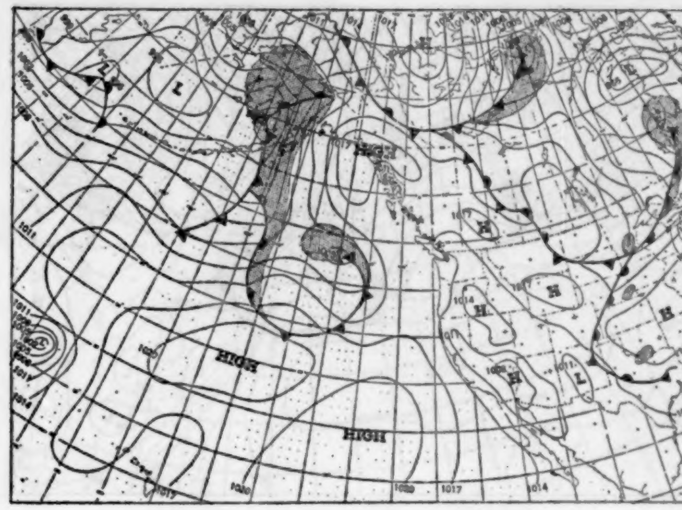

Figure 9.—Surface weather map for 0530 MST, August 21, 1950.

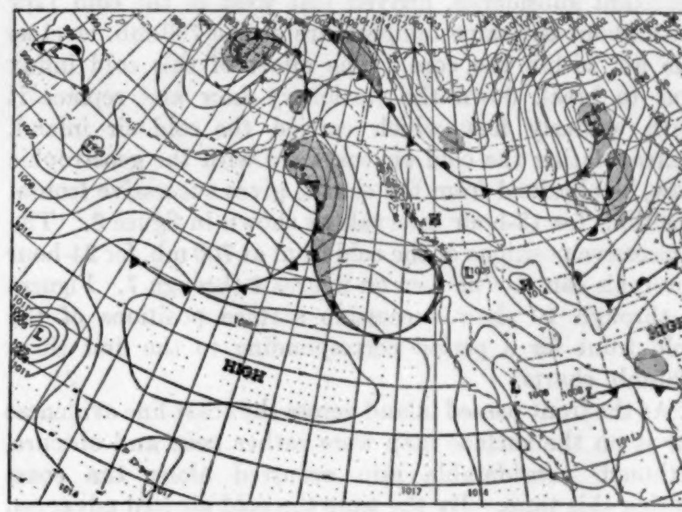

Figure 10.—Surface weather map for 0530 MST, August 22, 1950.

and 19th of August. The charts of 2330 MST, August 18 and 0530 MST, August 19, which have several ship reports in the area in question, show marked divergence of the isobars within the cold air. Strong divergence (in the hydrodynamical sense) was therefore occurring throughout the layer between 700 mb. and the surface.

As was noted above, the effect of this divergence is to cause the actual trajectory to depart from the constant vorticity trajectory in such a way that the actual path becomes increasingly anticyclonic with time. Therefore, instead of recurving northward the more southerly branch of the cold air outbreak continued in such a manner that the direction of flow was from the west-northwest. Consequently, the original cold outbreak was broken into two branches, one of which recurved to the north and the second of which flowed east-southeastward across the Pacific, south of the stationary ship at 50° N., 145° W. and, because of horizontal divergence and

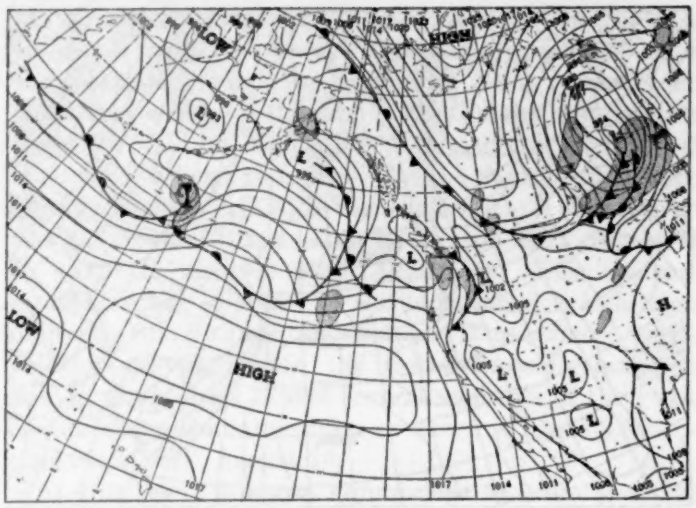

FIGURE 11.—Surface weather map for 1730 MST, August 22, 1950.

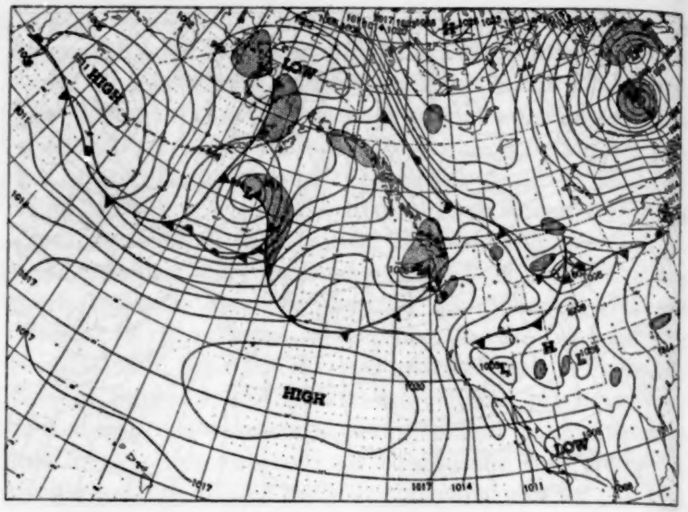

FIGURE 12.—Surface weather map for 1730 MST, August 23, 1950.

resultant subsidence, arrived just west of the cold Low with about the same temperature at the 700-mb. level as the air within the core. The affect of this cold influx was to break down the stationary Low and replace it with westerly flow which carried the cold air inland. Extrapolating the cold air eastward with the geostrophic flow, as obtained from the charts, gives successive frontal positions for 12-hour intervals as shown in figure 3. The successive positions of the cold front at 700 mb. for 24-hour intervals can also be seen on figures 4 through 7. Figures 8 through 10 show successive surface positions of the cold front for a period corresponding to the first three 700-mb. charts.

As the front passed inland across the coast line evidences for it on the surface map were rather poor and obscure, although considerable rain occurred along the coast during this time. By the time the cold air had advanced eastward as shown in figure 11, the front had become very marked and active accompanied by thunderstorms, sharp windshifts, marked pressure tendency differential, and sharp cooling. This was due largely to the great contrast which developed as the cool maritime air from the west came into contact with the very warm air east of the Cascades. In this connection it is well to point out that active surface fronts are not produced by this contrast in this area unless some outside influence changes the normal flow pattern and sets up active cold advection from the west.

Although thunderstorms accompanied the front as it moved eastward in the area east of the Cascades, amounts of precipitation produced by it were very light. This was to be expected since the cold air had lost a good deal of its moisture in passing over the Cascades and the warm air was of continental origin and therefore dry.

By 1730 MST of August 23 (see fig. 12) the cold air had covered the entire northern mountain area and the front had induced a wave in a polar continental front which had been moving slowly down from the north. The subsequent history of the Pacific front was short as it dissipated just east of the Continental Divide. Cold air advection continued, however, in the middle troposphere so that a squall line developed over western Kansas during the late evening of August 24 and the resultant shower activity continued in this area during most of the night. The mechanism of a squall line produced by the eastward advection of a relatively narrow tongue of cool air at intermediate heights is not self-perpetuating. This condition tends rather to destroy itself. The release of instability, which is a manifestation of the squall line, tends to destroy the cold tongue. The effect of the upward transport by convection of the heat realized by condensation tends likewise to destroy the tongue. In this manner the remnants of the cold surge were finally destroyed.

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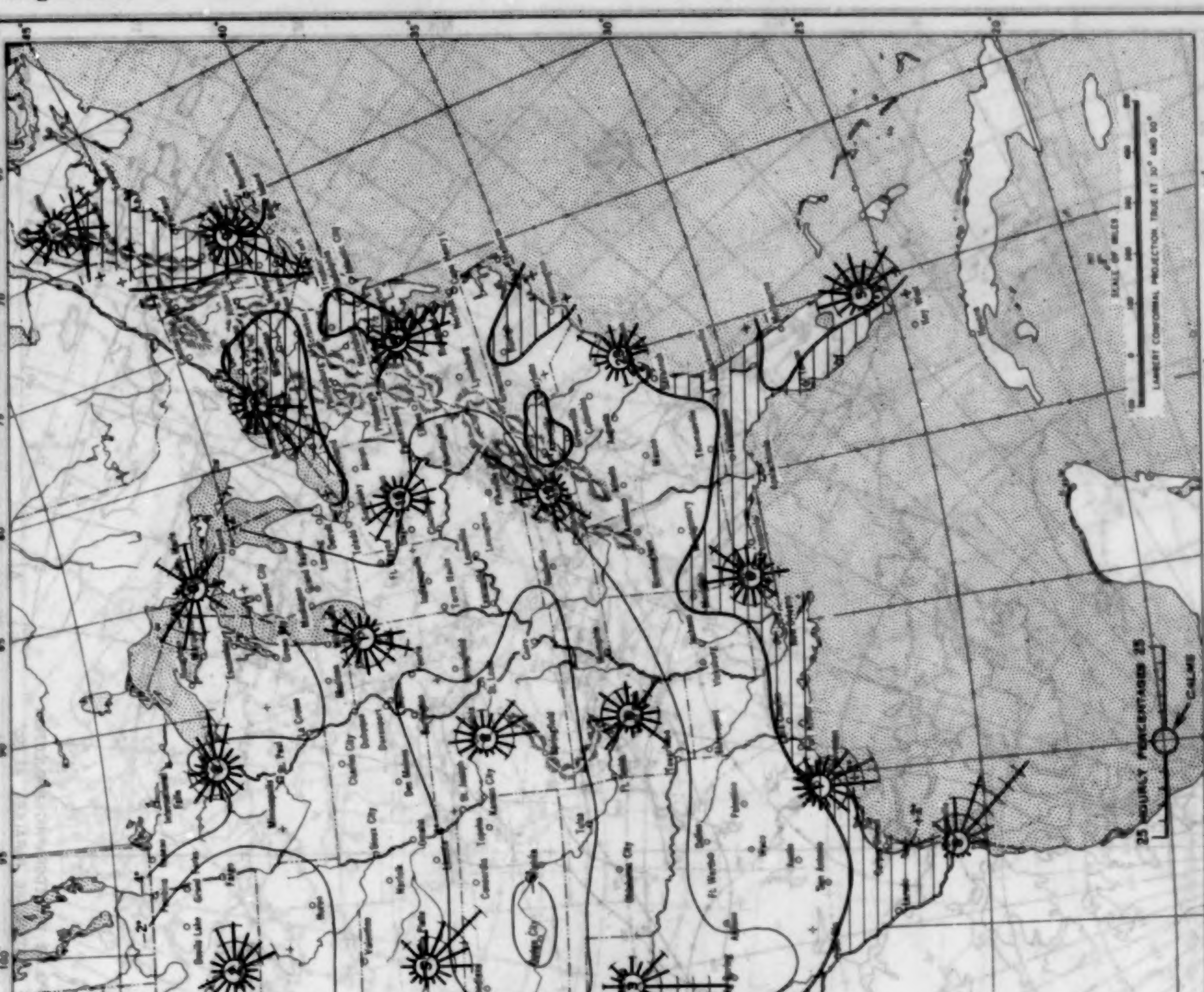
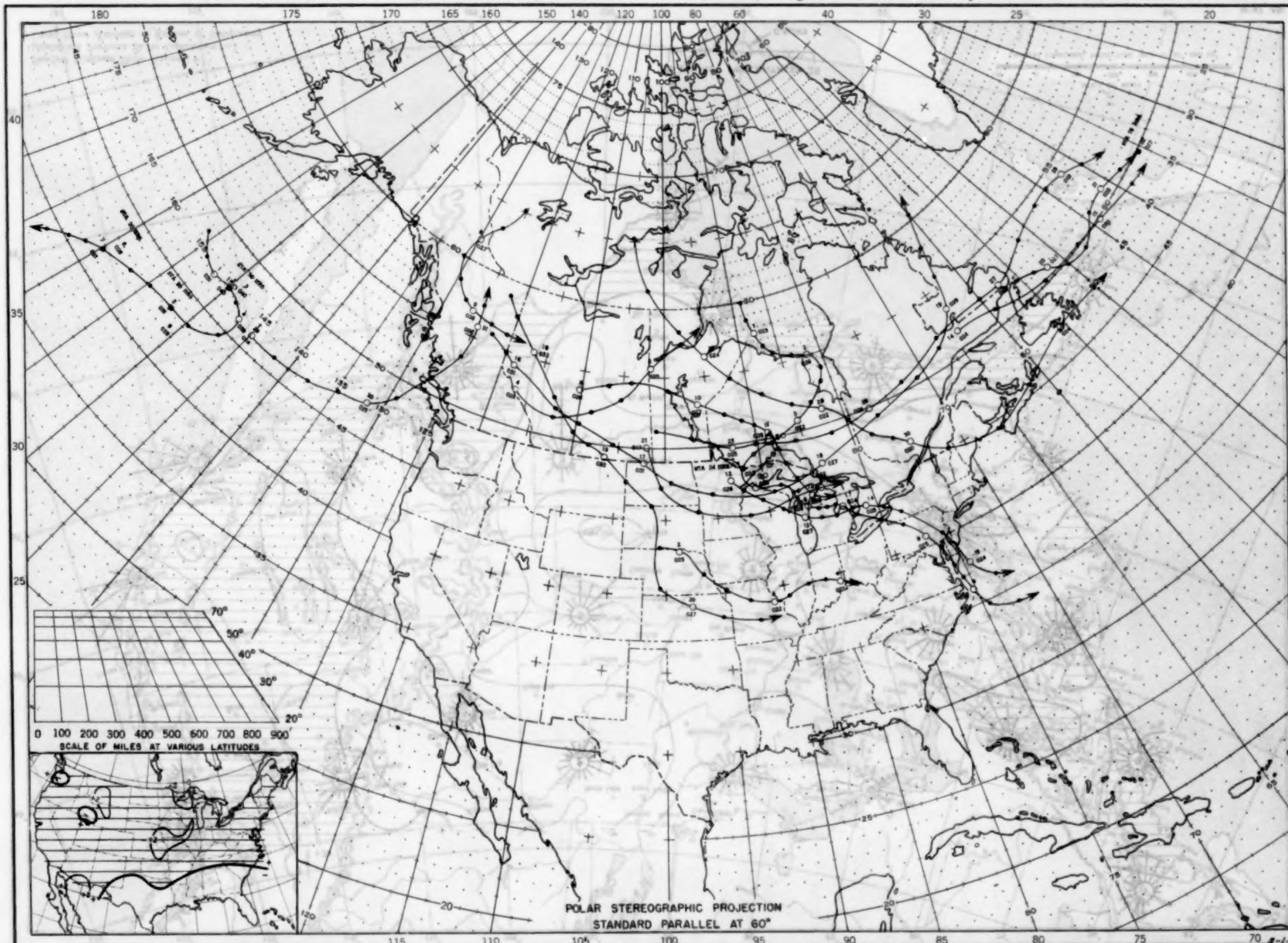


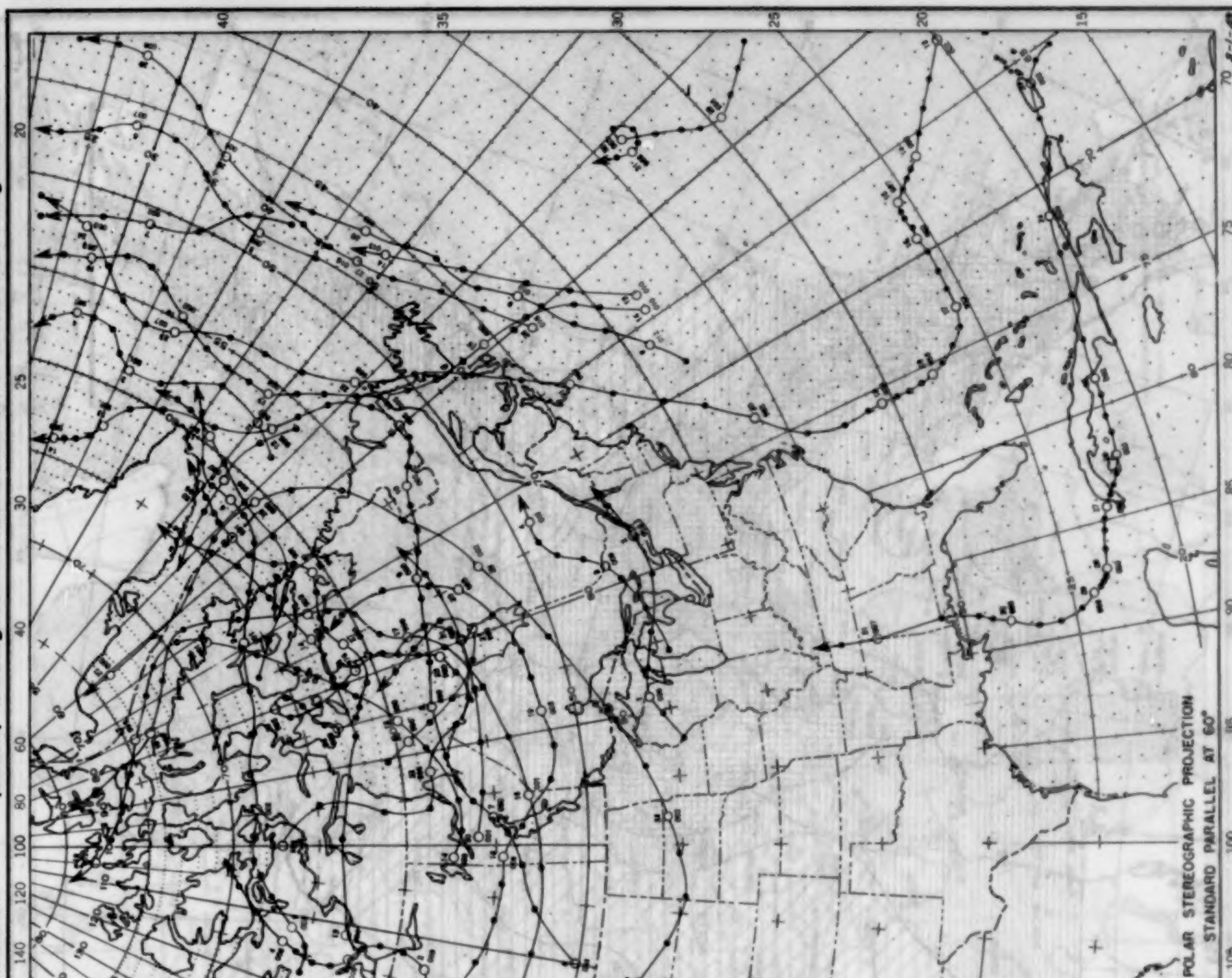
Chart I. Departure (°F.) of the Mean Temperature from the Normal, and Wind Roses for Selected Stations, August 1950

Chart II. Tracks of Centers of Anticyclones, August 1950. (Inset) Departure of Monthly Mean Pressure from Normal



Circle indicates position of anticyclone at 7:30 a. m. (75th meridian time). Dots indicate intervening 6-hourly positions. Figure above circle indicates date, and figure below, pressure to nearest millibar. Only those centers which could be identified for 24 hours or more are included.

Chart III. Tracks of Centers of Cyclones, August 1950. (Inset) Change in Mean Pressure from Preceding Month



Circle indicates position of cyclone at 7:30 a. m. (75th meridian time) Dots indicate intervening 6-hourly positions. Figure above circle indicates date, and figure below, pressure to nearest millibar. Only those centers which could be identified for 24 hours or more are included.

Chart IV. Percentage of Clear Sky Between Sunrise and Sunset, August 1950

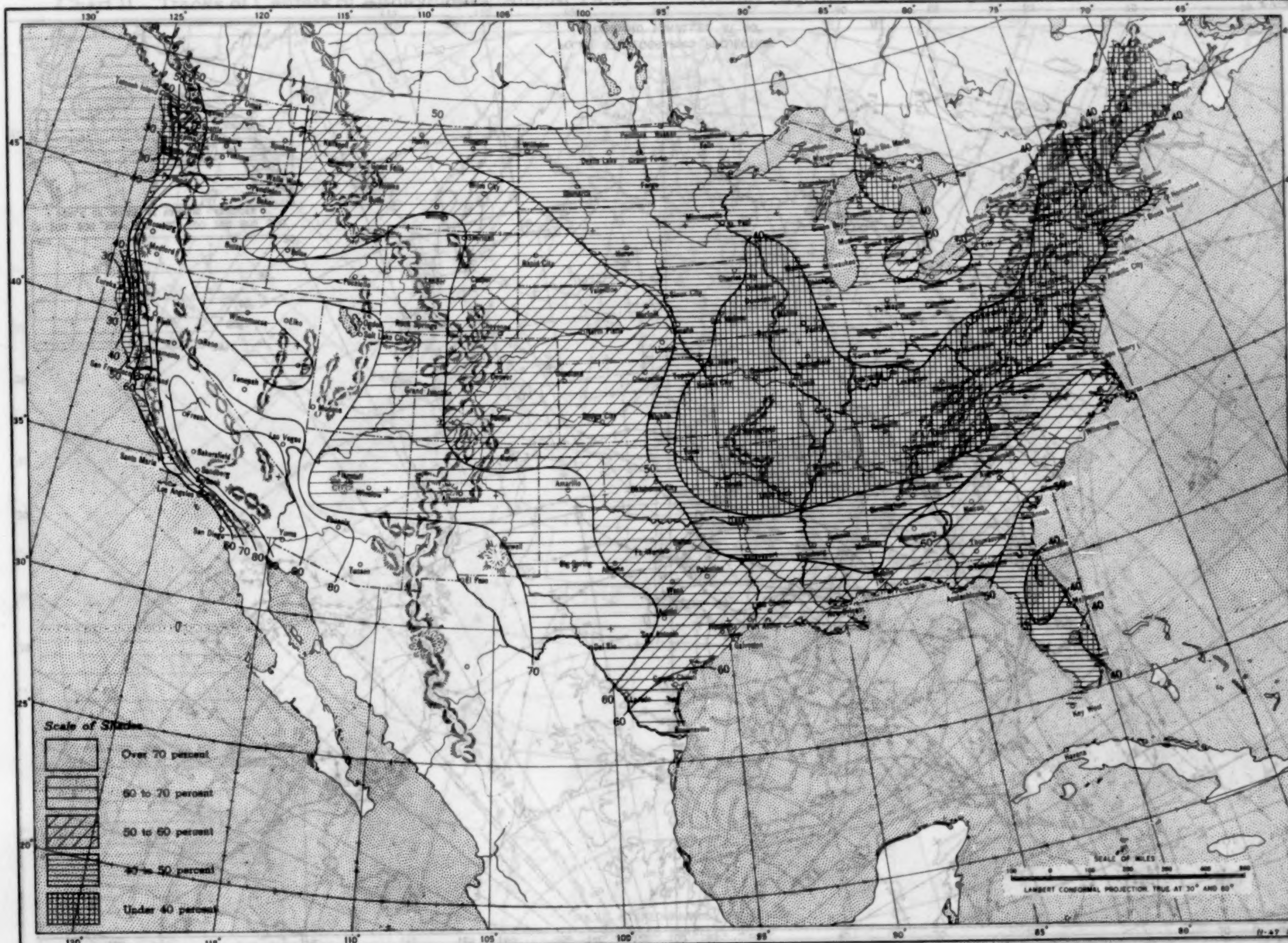


Chart V. Total Precipitation, Inches, August 1950.

(Inset) Departure of Precipitation from Normal

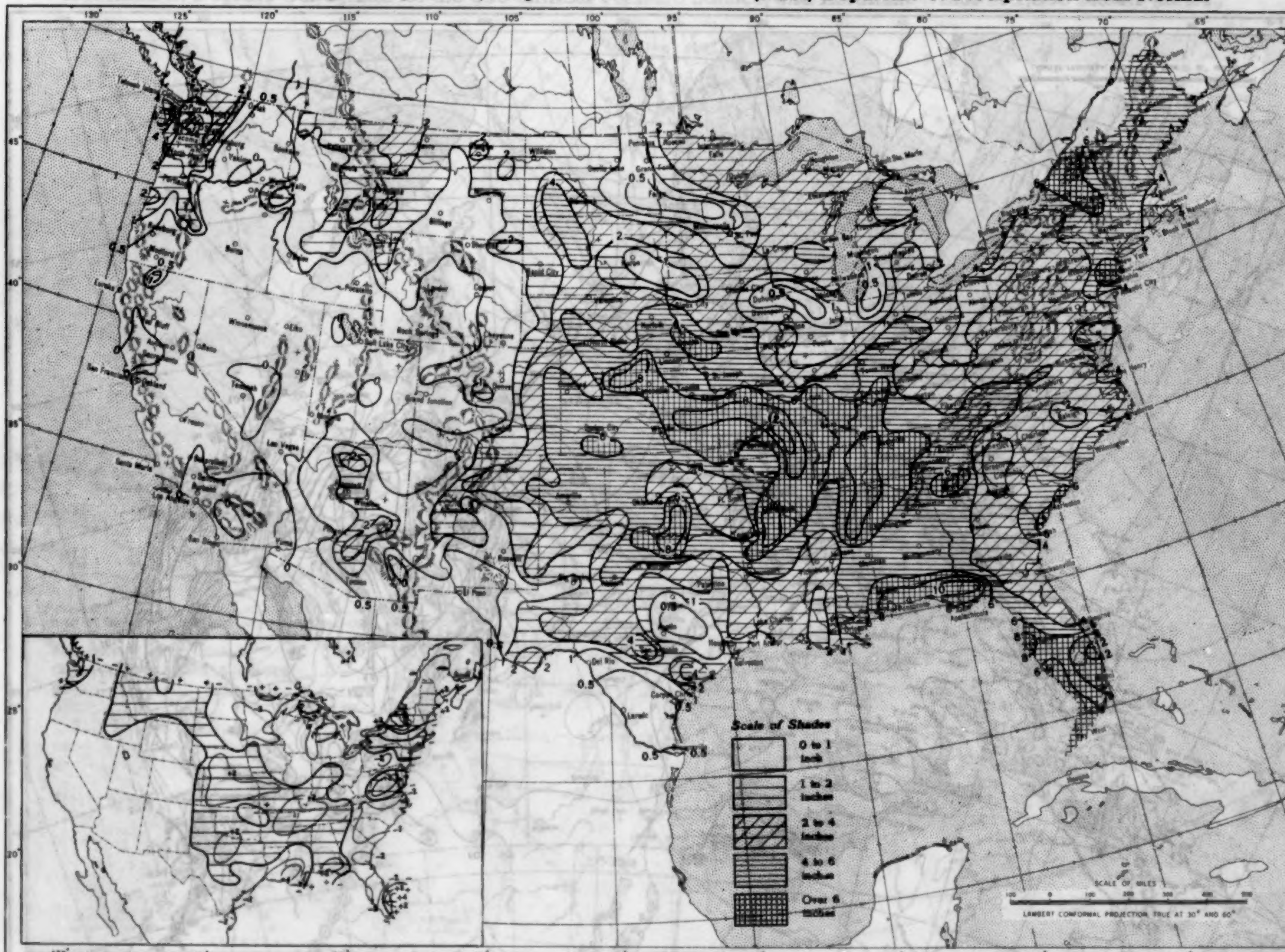


Chart VI. Mean Isobars (mb.) at Sea Level and Mean Isotherms (°F.) at Surface., August 1950

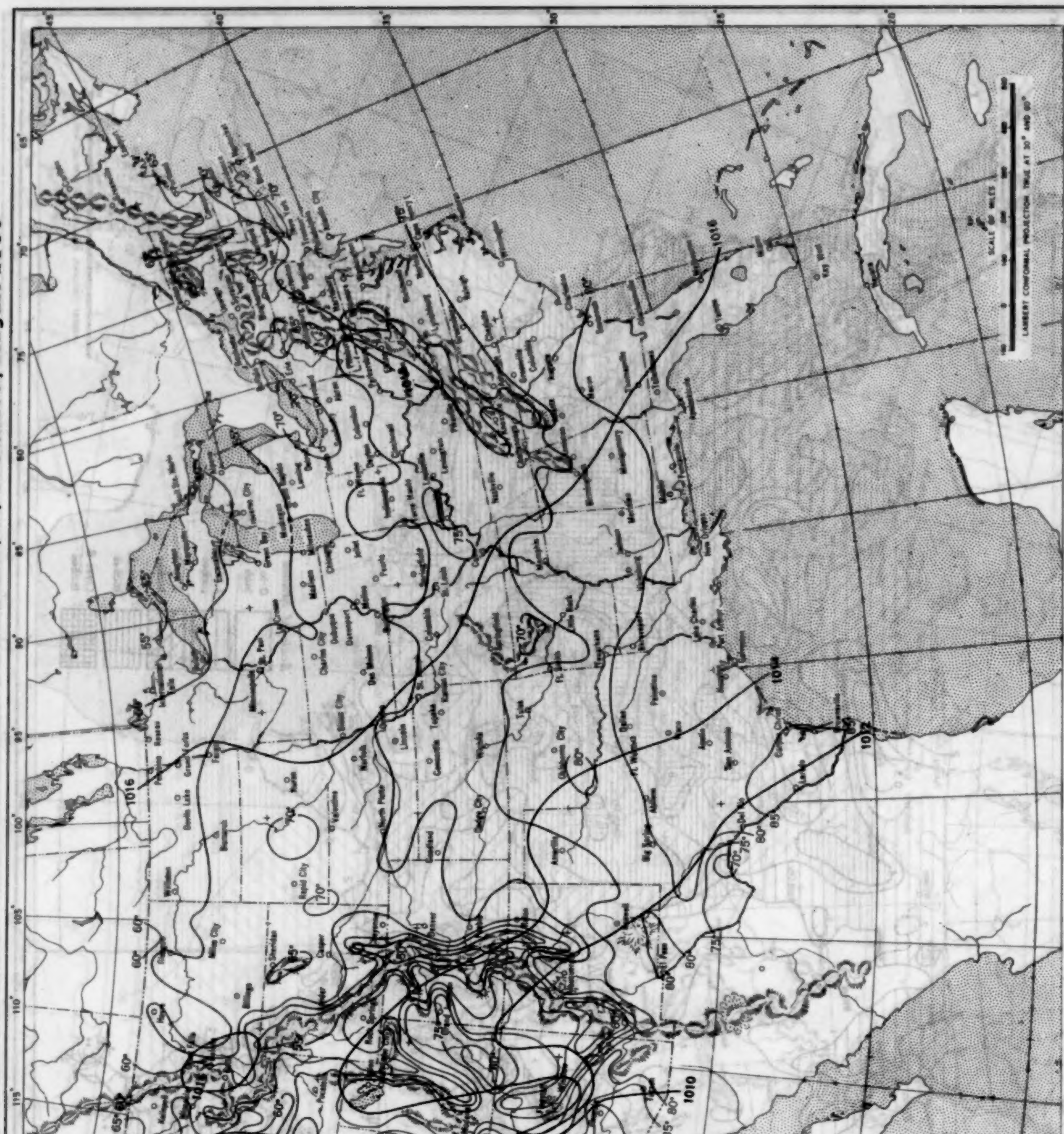
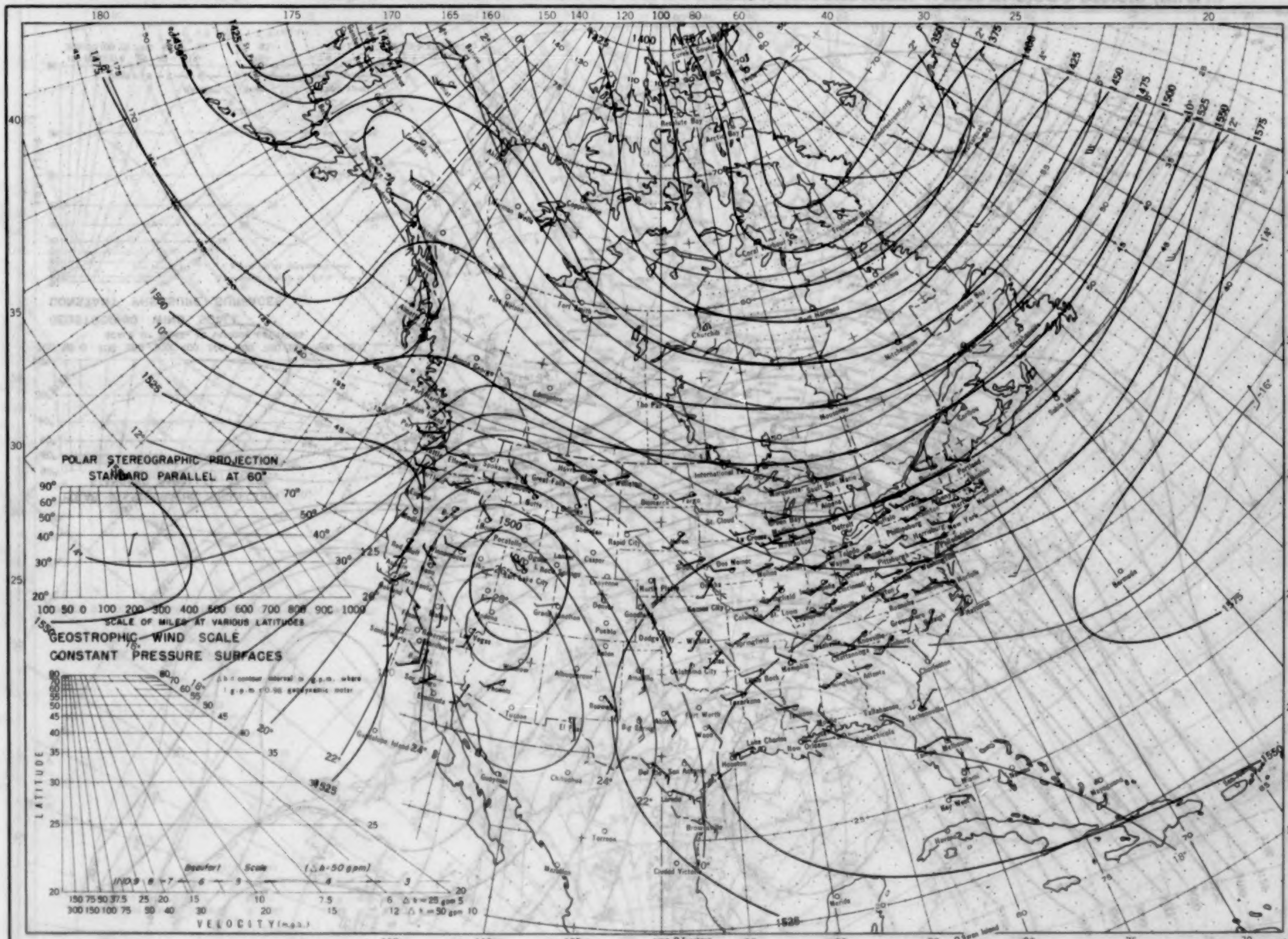
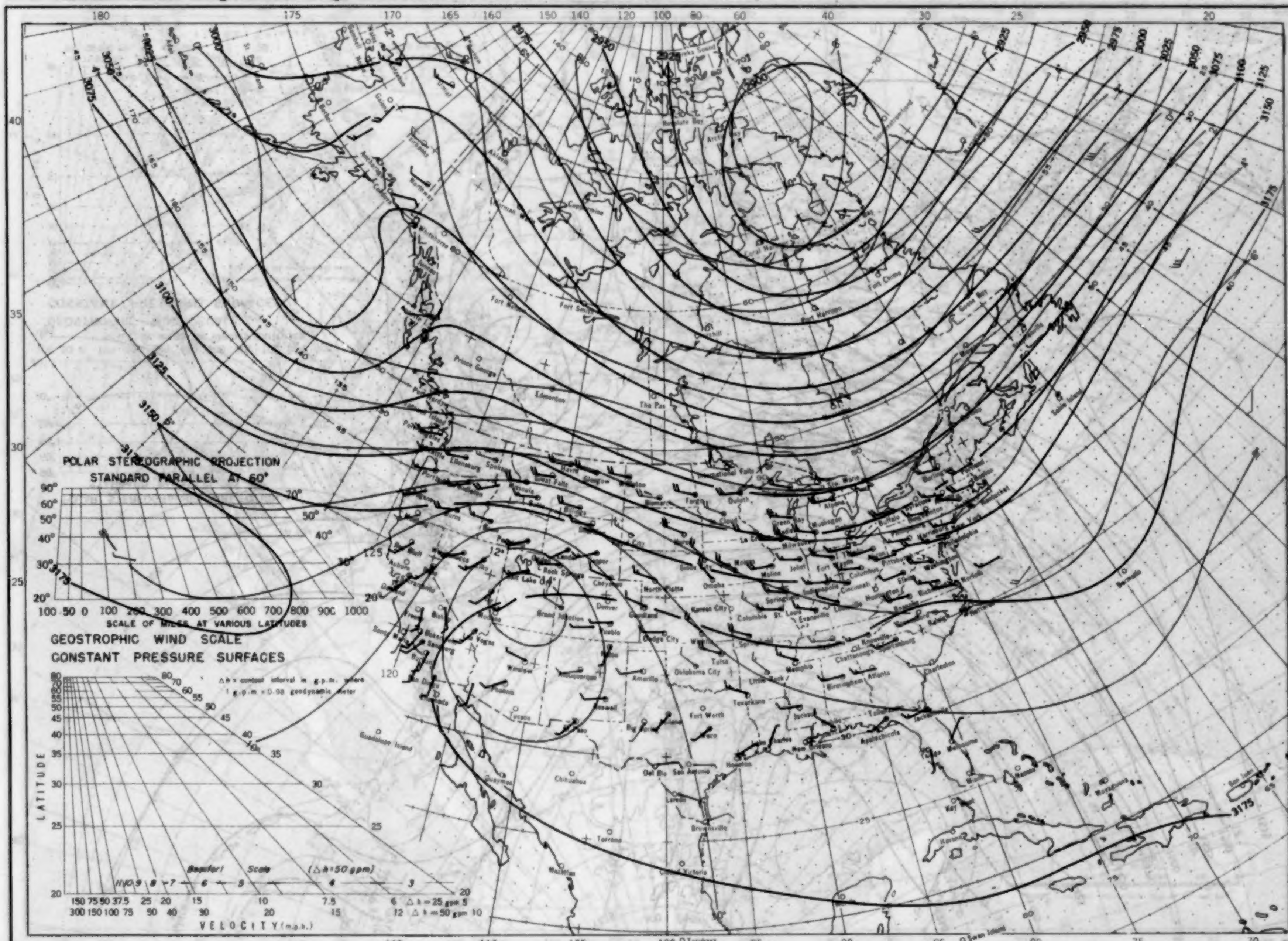


Chart VIII, August 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 850-millibar Pressure Surface, and Resultant Winds at 1,500 Meters (m. s. l.)



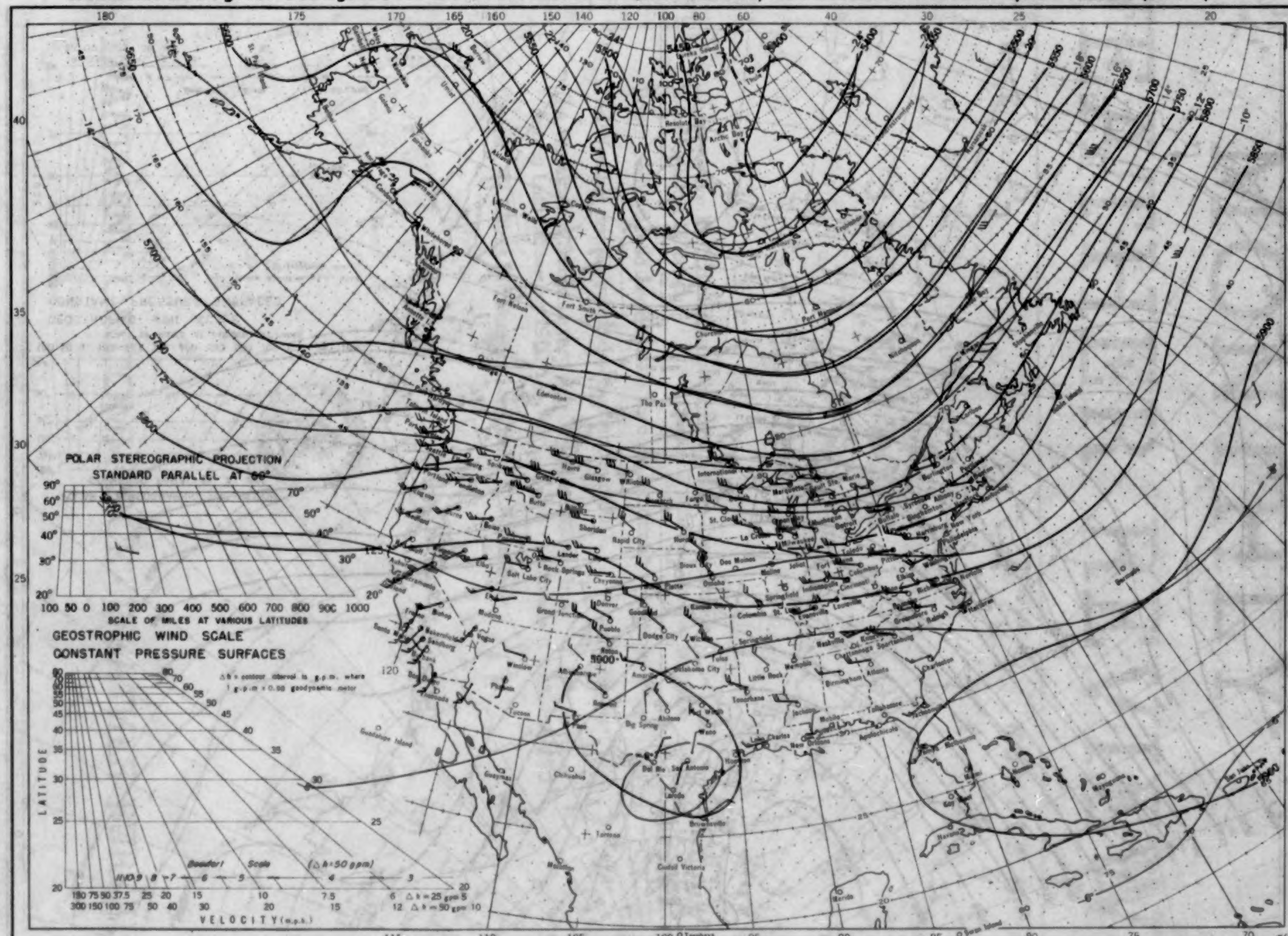
Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.

Chart IX, August 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 700-millibar Pressure Surface, and Resultant Winds at 3,000 Meters (m. s. l.)



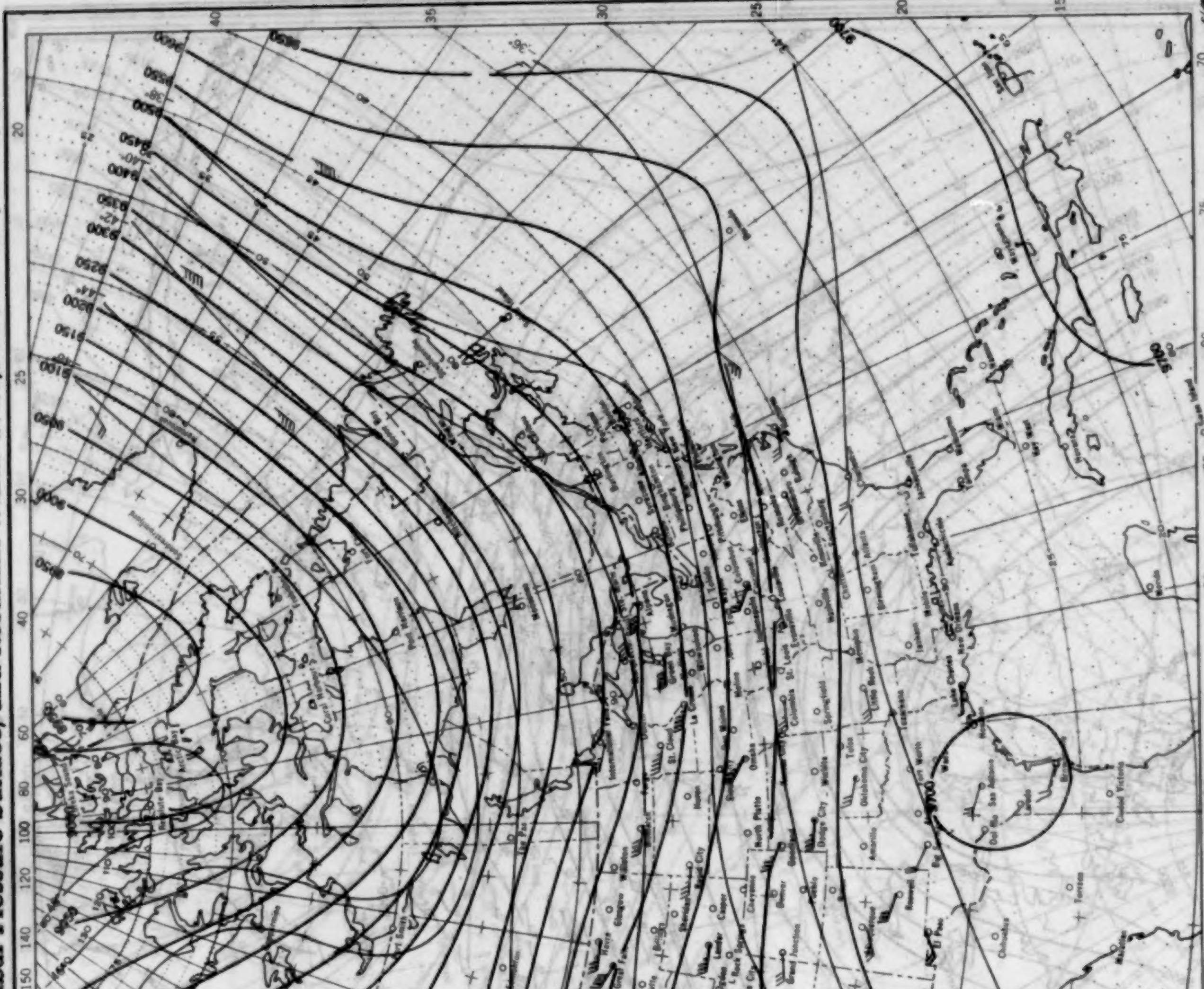
Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.

Chart X, August 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 500-millibar Pressure Surface, and Resultant Winds at 5,000 Meters (m. s. l.)



Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.

Chart XI, August 1950. Contour Lines of Mean Dynamic Height (Geopotential) in Units of 0.98 Dynamic Meters and Mean Isotherms in Degrees Centigrade for the 300-millibar Pressure Surface, and Resultant Winds at 10,000 Meters (m.s.l.)



Contour lines and isotherms based on radiosonde observations at 0300 G. C. T. Winds indicated by black arrows based on pilot balloon observations at 2100 G. C. T.; those indicated by red arrows based on rawins taken at 0300 G. C. T.